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Facilitating radiation leak detection: Designing a low-cost, wearable Geiger-Müller alarm for medical personnel

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Abstract

Occupational exposure to ionising radiation remains a major safety concern in imaging and nuclear medicine departments, where even small, unnoticed leaks from X-ray tubes, shielding defects, or mishandled radionuclides can accumulate into unnecessary dose for medical personnel. Conventional passive dosimeters provide only retrospective information, while commercial electronic personal dosimeters are often too costly to be deployed widely in resource-constrained healthcare systems. This paper presents the conceptual design of a low-cost, wearable radiation leak alarm intended to facilitate real-time leak detection for frontline medical personnel.The proposed device integrates a compact Geiger–Müller (GM) tube with a high-voltage bias circuit, a low-power ESP32 microcontroller, an OLED display, and a Li-Po battery in a lightweight clip-on enclosure. Firmware routines perform interrupt-based pulse counting, convert count rate into an approximate ambient dose-equivalent rate H*(10)H^*(10)H*(10), and trigger audible and visual alarms when user-defined dose-rate thresholds associated with potential leakage conditions are exceeded. A calibration and testing protocol is outlined using a low-activity potassium chloride check source and a traceable survey meter to derive a device-specific conversion factor between counts per minute and dose rate over the range relevant for leak detection.

While full experimental and clinical validation are planned as future work, the proposed architecture demonstrates a practical and affordable pathway towards complementing conventional passive dosimetry with real-time, wearable leak alarms, thereby strengthening radiation protection practices for medical personnel in low- and middle-income healthcare settings.

Keywords: radiation monitoring; Geiger–Müller tube; wearable dosimeter; medical personnel; clinical radiation safety; leak detection; real-time alarm; medical physics.

Introduction

Ionising radiation is a cornerstone of modern medical imaging and therapy, underpinning diagnostic X-ray, fluoroscopy, computed tomography (CT), nuclear medicine and hybrid imaging procedures that are performed daily in hospitals worldwide. At the same time, these modalities expose radiographers, interventional operators, nurses and other medical personnel to scattered and, in some cases, unintended radiation fields. International radiological protection bodies recommend strict occupational dose limits—typically an effective dose of 20 mSv per year on average over five years, with no single year exceeding 50 mSv and emphasise that occupational exposures should be kept “as low as reasonably achievable” (ALARA) while preserving clinical benefit.[1,2]

The foundation of occupational monitoring in many hospitals remains passive personal dosimetry, most commonly thermoluminescent dosimeters (TLDs) or optically stimulated luminescent (OSL) badges worn at the torso, collar or extremities.

These devices provide reliable, legally recognised estimates of cumulative dose over a monitoring period, but they are inherently retrospective: results may only become available weeks after exposure, long after any procedural or shielding problem could have been detected and corrected.[2,8]

Studies of staff working in X-ray imaging and interventional radiology have shown that doses to the eyes, hands and whole body can approach or exceed investigation levels in high-workload environments, and that better feedback during procedures would support adherence to ALARA principles and more effective optimisation of protection.[3,7] This has led to growing interest in real-time monitoring tools that can alert staff promptly when local dose rates become unusually high or when shielding or equipment performance is suboptimal.[3,7]

To address the limitations of purely passive monitoring, active electronic personal dosimeters (EPDs) and real-time dose-management systems have been introduced for staff directly involved in fluoroscopically guided interventions and other high-exposure tasks. These systems provide continuous readings of dose and dose rate, visual displays and audible alarms, and procedure-linked dose reports that can be used for optimisation and quality assurance, but their relatively high purchase and maintenance costs can limit widespread deployment, especially in resource-constrained hospitals.[3,9]

In parallel, the microelectronics and maker communities have demonstrated that compact Geiger–Müller (GM) tubes, high-voltage bias modules and low-cost microcontrollers can be combined to create affordable radiation survey meters and environmental monitors.

Recent developments in low-cost portable GM-based gamma monitors and custom dosimeters show that stable count-rate measurements and basic alarm thresholds can be implemented with modest hardware at a fraction of the cost of many commercial instruments.[4,11] Nevertheless, most of these designs are targeted at education, hobbyist background monitoring or environmental applications, rather than being engineered as wearable, clinically oriented leak alarms that integrate into the workflows and protection needs of medical personnel.[4,11]

Against this backdrop, there is a clear opportunity to explore how low-cost GM-based technology can be tailored to **facilitate radiation leak detection** for everyday users in clinical departments, complementing rather than replacing existing passive dosimetry and high-end EPDs. The present work therefore introduces the conceptual design of a low-cost, wearable Geiger–Müller-based radiation leak alarm intended for medical personnel in imaging and nuclear medicine environments, with the aim of providing an affordable early-warning layer that supports practical implementation of ALARA principles in routine clinical practice.[2,5].

Literature Review

Occupational radiation protection in medical imaging has traditionally relied on a combination of engineered controls (shielding and room design), administrative measures (time, distance and protective equipment) and passive personal dosimetry. This framework has been broadly effective in keeping staff doses within recommended limits, but several reviews have highlighted that unrecognised localised leakage, suboptimal shielding or poor technique in busy departments can still lead to elevated doses for certain staff groups.[1,7]

In response to these concerns, active electronic personal dosimeters (EPDs) and real-time dose-management systems have been introduced for staff who perform fluoroscopically guided procedures and other high-exposure tasks. EPDs provide continuous readings of dose and dose rate, visual displays and audio alarms, and can feed data into dose-management platforms that support optimisation, auditing and regulatory compliance.[3,9] However, the high capital and maintenance costs of these systems, together with the need for supporting software infrastructure, can limit their adoption in resource-constrained hospitals, where only a subset of staff may have access to such technology while the majority continue to rely solely on passive TLD/OSL services.[3,9]

A parallel line of technological development has emerged from low-cost and open-hardware radiation monitoring projects. These typically combine GM tubes, high-voltage modules and microcontrollers into compact survey meters or dosimeter prototypes aimed at environmental monitoring, education or personal safety. Demonstrations of solar-rechargeable dosimeters and portable digital gamma monitors show that simple hardware and firmware can deliver continuous count-rate measurements and basic alarm functionality at relatively low cost.[4,11] Nonetheless, such systems are rarely designed with clinical workflows, hospital infection-control requirements or occupational monitoring standards as primary constraints.[4,11]

In recent years, research on wearable or smart-badge dosimeters has gained momentum, exploring ways to integrate active radiation sensors into compact form factors that can be worn comfortably by staff and, in some cases, linked wirelessly to external displays or management systems. Reviews of wearable dosimetry technologies highlight the potential of such devices to provide more granular, real-time information about individual exposures in medical and defence applications, while also noting challenges related to cost, calibration and integration into existing protection frameworks.[5] Experimental evaluations of new real-time dosimeter sensors for interventional radiology staff further demonstrate that body-worn detectors can provide actionable feedback during procedures, but these systems often remain relatively complex and expensive compared with purely passive solutions.[10]

Beyond individual devices, Internet of Things (IoT) architectures for radiation monitoring have been proposed to collect, transmit and analyse dose or dose-rate data from multiple sensors distributed across occupational environments. Such systems can support centralised alerting, long-term trend analysis and integration with safety management platforms, but they typically require additional networking infrastructure, software and maintenance capabilities that may be difficult to sustain in low- and middle-income healthcare settings.[6] As a result, many institutions continue to face a trade-off between the simplicity and low cost of passive badges and the richer information provided by more sophisticated but resource-intensive monitoring solutions.[2,6].

Table 1 summarises the key characteristics of four representative approaches to occupational radiation monitoring: traditional passive badges, commercial EPDs, low-cost open GM counters and the low-cost wearable GM-based leak alarm proposed in this work. The comparison highlights the complementary roles of these systems and underscores the specific niche addressed by the proposed device.[1,3]

Table 1. Comparison of representative radiation monitoring approaches

Approach	**Main function**	**Real-time indication**	**Approximate cost per unit***	**Key limitations / notes**
Passive TLD/OSL badge	Regulatory cumulative dose monitoring	No (retrospective only)	Low–moderate (per badge + processing service)	Worn routinely, but results delayed; cannot warn during an ongoing leak or abnormal field.
Commercial electronic personal dosimeter	Real-time dose and dose-rate monitoring	Yes (display + audio alarms)	High	Technically robust, but relatively expensive; often available only to selected staff.
Low-cost open GM counter (desktop/handheld)	Survey or background radiation monitoring	Yes (basic count/alarm)	Low–moderate	Typically non-wearable; designed for education or environmental use, not clinical staff.

Proposed wearable GM leak alarm (this work)	Real-time leak detection for medical personnel	Yes (audio + visual alarm)	Target: low	Conceptual design; intended to complement passive badges and be affordable for wide deployment.

* Cost categories are indicative and depend on manufacturer, specifications and local procurement conditions.

Taken together, the literature indicates a clear gap between, on the one hand, low-cost but purely retrospective passive dosimetry and, on the other, sophisticated but relatively expensive active dosimetry and IoT-based monitoring systems. There is a need for intermediate solutions that provide real-time, easy-to-interpret leak alarms in a low-cost, wearable form factor that can be deployed widely among medical personnel, particularly in low- and middle-income countries. The present work addresses this gap by adapting low-cost GM-based technology into a wearable radiation leak alarm specifically tailored to the dose-rate ranges, usability constraints and resource limitations of clinical environments.[2,5] .

Methodology

The development of the proposed wearable radiation leak alarm followed an engineering design methodology structured around four main stages: definition of system requirements, hardware design and component selection, firmware and algorithm development, and specification of a calibration and testing protocol. The primary aim was to produce a conceptual design that is technically feasible, clinically relevant and economically affordable for deployment among medical personnel in routine imaging and nuclear medicine environments.[1]

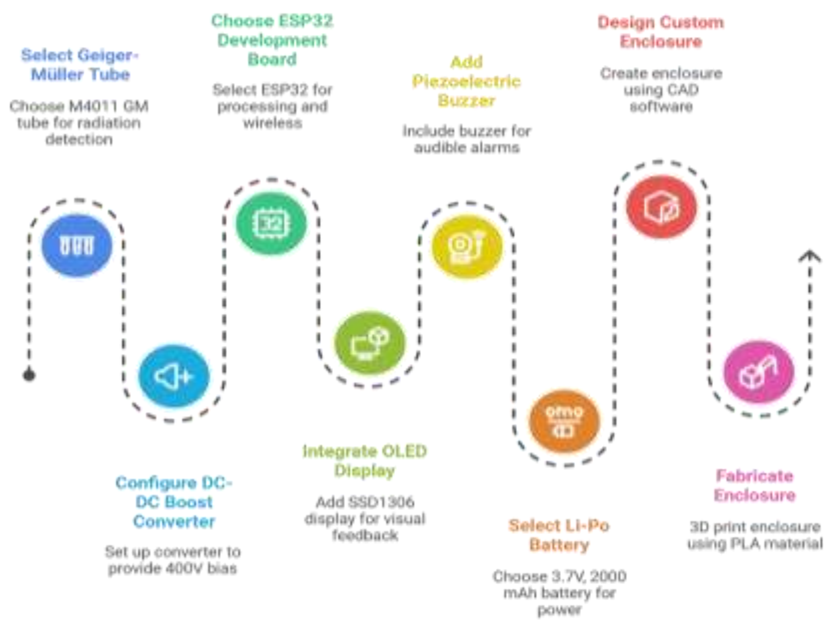
3.1 System Requirements and Design Specifications

Initial design criteria were formulated by considering clinical workflow constraints, typical dose-rate levels in medical environments, and user expectations for a wearable device. Functionally, the system is required to perform continuous monitoring of ambient gamma and beta radiation, provide an approximate real-time estimate of dose rate, and activate audible and visual alarms when a preset threshold associated with potential leakage conditions is exceeded. From a performance perspective, the device is intended to be sensitive to dose rates slightly above typical background (≈0.08–0.20 µSv/h) and to retain a reasonably linear response up to at least 5 µSv/h, covering the range of interest for detecting abnormal fields and localised leaks in clinical areas.[1,6]

User-centric specifications emphasised a compact, unobtrusive form factor suitable for clipping to a lab coat pocket, belt or lanyard, with a clear and minimal user interface requiring no calibration by the wearer. Operational requirements included an alert threshold nominally set at 0.30 µSv/h—high enough to avoid nuisance alarms from small background fluctuations yet low enough to highlight potential leakage or shielding problems—and a battery life target of at least 72 hours of intermittent monitoring, corresponding to multiple work shifts between charges. Economic requirements mandated exclusive use of readily available, low-cost components to keep the estimated unit cost within reach of resource-constrained institutions.[2]

3.2 Hardware Design and Component Selection

The core detection principle is based on a miniature Geiger–Müller (GM) tube selected for its robustness, simplicity and suitability for cost-sensitive applications.[6] An M4011 GM tube was chosen as the primary sensor, providing sensitivity to beta particles (≥0.2 MeV) and gamma photons with a relatively large effective detection area for its physical size. The tube is biased using a compact DC–DC boost converter configured to deliver approximately 400 V, which lies within the recommended operating plateau for this detector type and ensures stable pulse generation for ionising events.
An ESP32 development board serves as the main microcontroller unit (MCU), selected for its low-power modes, adequate processing capability for real-time pulse counting, and integrated wireless interfaces that could support future extensions such as data logging or remote monitoring. A 0.96-inch monochrome OLED display (SSD1306 driver) provides low-power visual feedback of dose-rate estimates and status icons, while a 5 V piezoelectric buzzer generates audible alarms when thresholds are exceeded. Power is supplied by a single-cell 3.7 V, 2000 mAh lithium-polymer (Li-Po) battery, managed by a TP4056-based charging and protection module that supports USB charging and includes over-discharge protection. The entire assembly is housed in a custom enclosure designed using computer-aided design (CAD) software and fabricated via fused deposition modelling (FDM) 3D printing in polylactic acid (PLA), with an integrated clip and optional wrist or lanyard attachment points to support different wearing preferences.[4,6].



Fieger 1: Hardware Design and Component Selection Process

3.3 Firmware Development and Algorithm Design

The device firmware was developed in C++ using the Arduino IDE toolchain for the ESP32 platform. The GM tube output pulses—sharp voltage transitions corresponding to individual ionisation events—are conditioned and fed to a digital interrupt pin on the MCU. An interrupt service routine (ISR) increments a pulse counter for each valid event, while simple debouncing logic suppresses spurious triggers due to electrical noise.

Dose-rate estimation is performed over a fixed integration window. Pulses are accumulated over 30 seconds to obtain a count per interval (CPI), which is then scaled to counts per minute (CPM). To convert CPM into an approximate ambient dose-equivalent rate H*(10)H^*(10)H*(10) in µSv/h, the firmware applies a calibration factor KKK such that:

$$. \frac{\mathrm{CPM}}{K} = \text{Dose rate } (\mu\mathrm{Sv/h})$$

The value of KKK is intended to be derived from a calibration procedure (Section 3.4) using a reference survey meter and a low-activity check source. The calculated dose rate is continuously compared with a predefined alert threshold (nominally 0.30 µSv/h). To reduce the likelihood of false alarms caused by short-term fluctuations or statistical noise, the firmware can require that the threshold be exceeded in two consecutive measurement cycles (equivalent to 60 seconds) before activating the alarm. When the alert condition is satisfied, the buzzer emits a repeating tone and the OLED display switches to a warning layout with a flashing dose-rate value to draw the wearer's attention. Low-power modes of the ESP32, including deep sleep between measurement intervals, are used to minimise energy consumption and extend battery life.[4,6]

3.4 Proposed Calibration and Testing Protocol

Because the device is intended as an **early-warning leak alarm** rather than a primary regulatory dosimeter, the calibration approach focuses on obtaining a reasonably accurate mapping between GM count rate and ambient dose-equivalent rate over the limited range of interest for clinical leakage detection. A practical protocol can be established using a traceable radiation survey meter as a reference instrument and a low-activity check source such as potassium chloride (KCl) or a sealed gamma source within the exemption-limit activity range.[1,6]

In the proposed procedure, both the wearable device and the reference meter are placed at fixed, reproducible distances from the check source in a controlled environment. For a series of source–detector geometries (for example, several distances spanning from near-background dose rates up to a few µSv/h), the reference meter's dose-rate readings would be recorded alongside the prototype's CPM values, averaged over multiple measurement intervals to reduce statistical fluctuations. A linear regression between CPM and reference dose-rate values would then be performed to derive the calibration factor KKK and to assess linearity within the target range. Additional qualitative tests could include background measurements in a low-radiation area, verification that the alert threshold is crossed for scenarios representative of potential leaks, and observation of device behaviour over extended operation to confirm stable power and user interface performance.[1,6]

Although full experimental implementation of this protocol and clinical field trials were beyond the scope of the present conceptual design, the methodology outlined here provides a clear pathway for future validation and refinement of the wearable GM-based leak alarm, including comparison with commercial electronic personal dosimeters and evaluation under realistic workload conditions in medical imaging departments.[3,6].

Results and Discussion

Because this work focuses on the conceptual design of a low-cost wearable Geiger–Müller leak alarm, the "results" are best expressed in terms of key design targets and expected performance parameters rather than measured experimental data. Table 2 summarises the main specifications derived from the hardware and firmware architecture described in Section 3, highlighting how the proposed device is intended to operate in typical clinical environments.[1,6]

Parameter / Feature	**Design target / Description**
Detector type	M4011 Geiger–Müller tube (beta/gamma sensitive)
Operating principle	Pulse counting of GM tube events with fixed integration window
Measurement interval	30 s integration window, converted to counts per minute (CPM)
Estimated dose-rate quantity	Ambient dose-equivalent rate H*(10)H^*(10)H*(10), derived from CPM via calibration factor KKK
Intended dose-rate range	Approx. 0.10–5.0 μSv/h (background to typical leak-detection range)
Default alarm threshold	0.30 μSv/h (configurable in firmware)
Alarm condition	Threshold exceeded in ≥ 2 consecutive measurement intervals (≈60 s)
User indicators	OLED display (numerical dose-rate + status icons), piezo buzzer (audible alarm)
Power source	3.7 V, 2000 mAh Li-Po battery with TP4056-based charging/protection
Target operating time per charge	≥ 72 h of intermittent monitoring using MCU low-power modes
Enclosure and form factor	Lightweight 3D-printed PLA housing with integrated clip and optional wrist/lanyard mount

Intended clinical use	Early-warning radiation leak alarm for medical personnel in imaging and nuclear medicine
Regulatory role	Complementary to passive TLD/OSL badges; not a replacement for formal dosimetry services

Table 2. Summary of key design targets for the proposed wearable GM-based leak alarm

The consolidated view in Table 2 illustrates how the proposed device is tailored to the specific niche of **real-time leak awareness** rather than precise regulatory dosimetry. By selecting an alarm threshold moderately above typical controlled-area background levels and focusing on dose rates up to a few μSv/h, the design targets conditions that may indicate shielding problems, equipment malfunctions or unusual scatter patterns, without generating frequent nuisance alarms during normal operation.[1]

The use of a fixed integration window and a simple CPM-to-dose-rate conversion based on a single calibration factor KKK reflects a deliberate trade-off between accuracy and simplicity. While more sophisticated spectrometric or energy-compensated detectors could offer improved quantitative performance, they would also increase complexity and cost, potentially undermining the goal of broad deployment in resource-constrained settings. In contrast, the GM-based approach seeks to provide an approximate but actionable indication of elevated radiation levels in a format that is easy for medical personnel to interpret.[3,6]

From a practical standpoint, the combination of low-power firmware strategies and a modest-capacity Li-Po battery is intended to support multi-shift operation without frequent charging, making it more likely that the device can be incorporated into daily routines. At the same time, the reliance on low-cost, widely available components and simple 3D-printed enclosures is designed to keep unit costs significantly below those of commercial electronic personal dosimeters, aligning with the aim of facilitating wider access to real-time radiation awareness.[2,4]

Within the broader context of occupational radiation monitoring, the parameters in Table 2 reinforce the complementary role of the proposed device. Passive TLD/OSL badges continue to provide reliable cumulative dose records over extended periods, and high-end EPDs remain the reference standard for detailed real-time dosimetry where resources allow.[1,3] The wearable GM-based leak alarm is positioned between these two extremes, offering a low-cost, easy-to-use early-warning layer that can help medical personnel recognise abnormal radiation conditions more quickly and respond in accordance with ALARA principles.[2–4]

Although experimental calibration data and clinical field trials are not yet available, the design targets summarised in Table 2, combined with the calibration and testing protocol outlined in Section 3.4, define a clear roadmap for future validation. Subsequent work can quantify linearity, calibration uncertainty, alarm response characteristics and user acceptance under realistic clinical conditions, and can explore enhancements such as wireless data logging or integration with dose-management systems.[3,5,6].

Limitations and Future Research Directions

Although the proposed wearable Geiger–Müller-based leak alarm offers a promising low-cost approach to enhancing real-time radiation awareness among medical personnel, several limitations of the present work must be acknowledged. First, the current study is primarily conceptual and does not yet include experimental calibration data or clinical field trials. As a result, key performance parameters—such as the accuracy of dose-rate estimates, linearity over the intended dose-rate range and long-term stability—remain to be quantified under controlled laboratory and clinical conditions.[3,6]

Second, the device relies on a single GM tube with an integrated response to gamma and higher-energy beta radiation, without explicit energy or particle discrimination. This simplifies the hardware but may introduce energy-dependence in the CPM-to-dose-rate relationship outside the calibration conditions, particularly in mixed radiation fields. Third, advanced features commonly found in commercial electronic personal dosimeters—such as onboard data logging, wireless connectivity, integration with dose-management software and robust industrial enclosures—are not yet implemented in the conceptual design, which may limit traceability and long-term record-keeping in its current form.[3,5]

A further limitation is that the user-interface design and alarm logic have not yet been evaluated through human-factors studies. Practical questions—including alarm audibility in noisy clinical environments, the risk of alarm fatigue, the optimal choice of threshold levels and the acceptability of the device to different staff groups—remain open. In addition, the current design has been tailored primarily to general imaging and nuclear medicine contexts and does not explicitly address more demanding interventional radiology or cardiology scenarios, where dose rates and workflow requirements may differ significantly.[1,3]

These limitations define a clear agenda for future research. A first priority is the experimental implementation of the calibration and testing protocol outlined in Section 3.4, using a traceable survey meter and suitable check sources to derive a device-specific calibration factor, characterise linearity, estimate calibration uncertainty and compare performance against commercial electronic personal dosimeters.[3,6] Subsequent clinical pilot studies in one or more imaging and nuclear medicine departments could then assess user acceptance, alarm effectiveness and the impact of the device on radiation protection practices in real workflows.

Further work may also explore design enhancements such as adding low-power wireless connectivity (e.g. Bluetooth Low Energy) for optional integration with central monitoring or dose-management platforms, implementing basic data logging for retrospective analysis, and refining the enclosure to improve robustness, splash resistance and ease of cleaning. Finally, it would be valuable to investigate variations of the design tailored to specific use cases such as interventional suites, mobile radiography or education and training while maintaining the core objective of providing an affordable, wearable early-warning layer that complements existing passive dosimetry services, particularly in low- and middle-income healthcare settings.[2–5]

Conclusion

This work has presented the conceptual design of a low-cost, wearable Geiger–Müller-based radiation leak alarm intended to facilitate real-time detection of abnormal radiation fields for medical personnel working in imaging and nuclear medicine environments. Motivated by the limitations of purely retrospective passive dosimetry and the high cost of commercial electronic personal dosimeters, the proposed device aims to provide an intermediate, affordable early-warning layer that can be deployed more widely, particularly in resource-constrained healthcare systems.[1–3]

The design integrates an M4011 Geiger–Müller tube, a compact high-voltage supply, an ESP32 microcontroller, a small OLED display, a piezoelectric buzzer and a rechargeable Li-Po battery in a lightweight clip-on enclosure. Firmware routines implement interrupt-based pulse counting, conversion of count rates into an approximate ambient dose-equivalent rate H*(10)H^*(10)H*(10) using a calibration factor, and threshold-based alarm logic tailored to the dose-rate ranges relevant for leak detection in controlled medical areas. A practical calibration and testing protocol has been outlined using a traceable survey meter and a low-activity check source, providing a clear pathway for future experimental characterisation of linearity, calibration uncertainty and alarm behaviour.[3,6]

Although the present study does not yet include experimental calibration data or clinical field trials, the consolidated design targets and methodological framework indicate that a technically feasible and economically accessible wearable leak alarm can be realised using widely available components and straightforward fabrication methods. Future work will need to validate the device quantitatively, assess user acceptance and explore enhancements such as wireless connectivity and integration with dose-management systems. If successfully implemented and adopted, such a device could help democratise access to real-time radiation awareness, support earlier identification of abnormal radiation conditions and contribute to the practical application of ALARA principles in everyday clinical practice, especially in low- and middle-income healthcare settings.[1–4]

References

[1] International Commission on Radiological Protection. (2007). *The 2007 recommendations of the International Commission on Radiological Protection* (ICRP Publication 103). *Annals of the ICRP, 37*(2–4), 1–332.

[2] International Atomic Energy Agency. (2014). *Radiation protection and safety of radiation sources: International basic safety standards* (IAEA Safety Standards Series No. GSR Part 3). Vienna, Austria: Author.

[3] Miller, D. L., Vañó, E., Bartal, G., Balter, S., Dixon, R., Padovani, R., Schueler, B., Cardella, J. F., & De Baère, T. (2010). Occupational radiation protection in interventional radiology: A joint guideline of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology. *Journal of Vascular and Interventional Radiology, 21*(5), 607–615. https://doi.org/10.1016/j.jvir.2010.01.007

[4] Guo, C.-Y., Lu, K.-T., Chen, C.-Y., & Hsieh, M.-C. (2022). A solar-rechargeable radiation dosimeter design for environmental monitoring. *Chemosensors, 10*(3), 27. https://doi.org/10.3390/chemosensors10030027

[5] Dhanekar, S., & Rangra, K. J. (2021). Wearable dosimeters for medical and defence applications: A state-of-the-art review. *Advanced Materials Technologies, 6*(6), 2000895. https://doi.org/10.1002/admt.202000895

[6] Suryaningtyas, E. A., Adi, K., Dartini, D., & Wibowo, G. M. (2023). Internet of Things (IoT)-based radiation exposure monitoring system: Data collection, analysis, and alerting in occupational environments. *Journal of Physics: Conference Series, 2600*(1), 012022. https://doi.org/10.1088/1742-6596/2600/1/012022

[7] Le Heron, J., Padovani, R., Smith, I., & Czarwinski, R. (2010). Radiation protection of medical staff. *European Journal of Radiology*, *76*(1), 20–23. https://doi.org/10.1016/j.ejrad.2010.06.034

[8] Martin, C. J. (2009). A review of radiology staff doses and dose monitoring requirements. *Radiation Protection Dosimetry*, *136*(3), 140–157. https://doi.org/10.1093/rpd/ncp168

[9] Vañó, E., Fernández-Soto, J. M., Sánchez-Casanueva, R. M., & Ten, J. I. (2023). Patient and occupational doses for interventional radiology procedures integrated into a dose management system. *British Journal of Radiology*, *96*(1143), 20220607. https://doi.org/10.1259/bjr.20220607

[10] Hattori, K., Inaba, Y., Kato, T., Fujisawa, M., Yasuno, H., Yamada, A., & Chida, K. (2023). Evaluation of a new real-time dosimeter sensor for interventional radiology staff. *Sensors*, *23*(1), 512. https://doi.org/10.3390/s23010512

[11] Luvsanbat, K., Turtogtokh, T., Begzsuren, T., Enerelt, U., Gerelmaa, O., & Erdenebaatar, D. (2024). Development of RAD1, low-cost, portable, digital gamma radiation monitor. *Physics*, *35*(594), Article 6806. https://doi.org/10.22353/physics.v35i594.6806