

Development of a Smart Radiation Monitoring System for Occupational Safety in Healthcare Facilities

Kimberly Long Holt

Health and Safety Concepts – Environmental Safety & Health

Corresponding Author: Kimberly Long Holt ka3027@yahoo.com

ARTICLE INFO

Keywords: Smart Radiation Monitoring, IoT System, Healthcare Facilities, Real-Time Radiation Detection, Radiation Safety Protocols

Received : 20, May

Revised : 22, June

Accepted: 24, July

©2025 Holt: This is an open-access article distributed under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/).



ABSTRACT

This paper will propose a smart radiation monitoring system that could help improve healthcare occupational safety by decreasing ionizing radiation. The system combines Geiger-Muller and semiconductor sensors with wireless communication protocols, such as Wi-Fi and the LoRaWAN interface, to monitor them in real time. The system offers immediate feedback through cloud-based dashboards and runs automatic alerts on exposure limits via IoT-based technologies. Stationary and wearable sensors positioned across several hospital departments had their real-time data processed and analyzed by machine learning schemes to identify abnormalities and predict exposure risks. In a pilot study, a 32.5% decline in worker exposure was observed after 30 days, reflecting the benefit of the system in enhancing radiation safety and compliance with international requirements regarding radiation protection.

INTRODUCTION

In many areas of healthcare today such as imaging, radiotherapy and nuclear medicine, radiation is a vital aid. Although these new technologies greatly help in patient care, they also increase hazards to workers in the healthcare field (WHO, 2021). Being exposed to ionizing radiation for a long time, even at low amounts, can cause cancer, eye problems and changes in genetic material (ICRP, 2020). Therefore, there is an increasing need for systems that can monitor radiation instantly and help cut down exposure experienced by medical staff.

Previously, passive dosimeters such as thermoluminescent dosimeters (TLDs) and film badges were what people relied on for radiation monitoring. Even though there are many such devices, they only give data after the fact and are held back by slow feedback, manual recording and keeping the records inaccessible to others (Andreo et al., 2017). Delay between exposure and reporting can be quite dangerous in places like interventional radiology and oncology departments. Besides, not having contextual data and using manual processes often leads to delayed safety actions, putting employees at more risk.

Over the past few years, greater use of Internet of Things (IoT) technologies has provided new ways to improve occupational safety. Using IoT, various systems can work together to gather, handle and send information immediately, providing stronger awareness of events as they happen (Atzori et al., 2010). Together with radiation detection resources, IoT allows close monitoring, informs decisions with data and gives automatic alerts on safety. When sensor technology, wireless communication and data analytics are used as part of IoT, this could improve protection from unwanted radiation exposure in healthcare.

The Manufacturer Requires a Smart Radiation Monitoring System

Health facilities that treat patients with radiology, nuclear medicine and oncology daily consist of high-exposure areas. Radiologic technologists, interventional radiologists and medical physicists run a higher risk of being exposed at work (McCaffrey et al., 2018). Despite regulations from both the ICRP and the IAEA, making sure exposure is under limits and safety practices are put in place is not always practiced in real-time (ICRP, 2020; IAEA, 2014).

A capable radiation monitoring system closes this void by sending real-time reports about radiation, worker positions and the environment. Its real-time information helps with immediate responses and it can also be used to analyze changes over a period of time. In rapidly changing or intense medical situations, traditional systems struggle to provide such dynamic feedback which limits their usefulness.

The Basic Tools for System Development

A smart radiation monitoring system can be built using sensor technology, wireless data transfer, data processing and safety rules.

1. Sensor Technology

A monitoring system relies on radiation sensors that can spot X-rays, gamma rays and beta particles. Silicon PIN diodes, cadmium zinc telluride (CZT) and scintillation detectors are very useful since they are both sensitive and compact (Zhang et al., 2020). Having both wearable and stationary sensors allows for monitoring people and the environment. They are always measuring both the instant dose and the total exposure, reporting values on a second-to-second schedule.

2. Wireless Communication

A network of sensors is set up to use Zigbee, Wi-Fi and LoRaWAN which are all low-energy wireless communication systems. Efficient data transfer using little power is made possible by these protocols which helps wearable devices last longer (Kumar & Lee, 2019). Because of wireless connectivity, sensor networks can be put in place without the challenge of wired setup and all the captured data is sent straight to a central screen in real time.

3. Data Analytics

The processed data are then handled with advanced math and technology, including searching for unusual events, patterns and prediction methods. Cloud platforms allow radiation safety officers and hospital administrators to track exposure in all areas, find the most dangerous regions and act quickly if needed (Chen et al., 2021). It is possible for safety managers to act ahead with the use of machine learning algorithms that learn from historical data and users' behaviors.

4. Safety Protocols

When these technologies are used in healthcare institutions, everyone must follow strict safety and regulatory rules. The system meets both the ICRP recommendations and the laws and guidelines given by national organizations. If the amount of radiation is too high, a system alert is sent to clear the area, increase shelter security or adjust the way radiological procedures are done. Having roles determine who can access monitoring data supports privacy and ethical standards.

Aims and Objectives

The goal of this research is to create, test and improve an IoT-based system for monitoring radiation in healthcare places to boost safety. The overall idea is to improve traditional radiation safety by using current monitoring, smart processing of data and automatic warnings.

The detailed objectives are:

1. Developing a modular system that uses current sensors able to spot various forms of ionizing radiation accurately.
2. Building a system that lets radiation data be transmitted from remote areas to a centralized radio station in real time.
3. To apply data analytics systems that let users take immediate actions, analyze market trends and apply models to improve workplace safety.
4. To put regulatory safety measures in place and ensure the system follows rules for radiation protection in healthcare everywhere.
5. To check how well the system works, one should test reliability, check how it can be used and review if it can help lessen radiation exposure at work.

By completing these tasks, the research tries to offer a reliable, adaptable and human-centered tool for increasing safety during radiation in hospitals and similar settings. Such a system would protect healthcare staff and also make it possible to handle operations more efficiently where radiation is consistently used.

LITERATURE REVIEW

Diagnosis and treatment of diseases have advanced a lot with the help of ionizing radiation in healthcare. The dangers of working with radiation often still worry health officials. The literature review reviews current radiation detection systems, new generated research, how IoT is applied in healthcare, analysis of large volumes of radiation data and examples of standard operating safety procedures. It mentions the research gap that the smart radiation monitoring system intends to fix.

Dealing with Radiation in Healthcare Areas

Professionals in radiology, cardiology, oncology and nuclear medicine deal with radiation almost every day. In line with WHO data, (2021), prolonged exposure to some agents for a long time, even when it stays beneath allowed levels, is related to an increased risk of leukemia, thyroid cancer, eye damage and genetic effects. For workers, the ICRP (2020) advises a yearly average of 20 mSv over 5 years, ensuring that no one year is more than 50 mSv. Even though these guidelines exist, not having real-time monitoring can still cause unnoticed overexposures during high-risk procedures involving fluoroscopy (Rehani et al., 2018).

Problems with Conventional Sensor Networks

Personal dosimeters such as thermoluminescent dosimeters (TLDs), optically stimulated luminescent dosimeters (OSLDs) and film badges, are traditional monitoring devices for radiation. Since they save money and are in line with regulations, these devices are commonly applied by many companies (Andreo et al., 2017). But one main disadvantage is that data are studied periodically and not in real time. The delay prevents workers from receiving quick help after being exposed which may cause safety issues (McCaffrey et al., 2018). Also, these devices do not gather enough information to find out about exposure sources or how long the exposure has lasted.

In addition, fixed environmental radiation monitors in radiology rooms are not able to provide personal reports of workers' doses. As explained by Liu et al. (2020), when people in healthcare move from place to place, the exposure to chemicals may not be accurately measured by fixed systems.

Improvements in Sensors Used for Detecting Radiation

Modern radiation sensors are based on advances in sensor innovation. Having considered radiation readings, cadmium zinc telluride (CZT), silicon PIN photodiodes, and gallium arsenide devices can gather more information than the type of technology used in the past (Geiger-Muller tubes) and can also be made small (Zhang et al., 2020). This is because the sensors can be quite readily applied by transferring them to wearable devices because they are incredibly small and require a low amount of power to be functional.

Also, due to advances in materials such as sodium iodide (NaI) and cesium iodide (CsI), scintillation detectors have now grown increasingly reliable when it comes to exceptional gamma spectroscopy, which has helped in the detection and identifying isotopes (Manikandan et al., 2021). Through these renovations, the authorities are now in a better position to identify and examine the type of radiation and also determine its source.

Combining several types of sensors into a single wearable item makes it more precise and powerful. The latter is well illustrated by a hybrid sensor comprised of scintillation and semiconductor subunits capable of detecting both high-energy and low-energy light owing to its broad spectrum (Chen et al., 2021). The devices need calibration, and the interference with the environment and Long-term stability remains a question of clinical application.

The use of IoT and Wireless in Radiation Monitoring

Because of the Internet of Things (IoT), it is now much simpler to monitor environmental and work-related parameters. With IoT, sensing, sending data and monitoring from a distance can take place instantaneously which matters a lot in rapidly changing health care. Atzori et al. (2010) state that IoT helps make environments "smart" by connecting sensing devices and providing quick data analysis for better decisions.

Radiation safety can be improved with IoT by providing employees with devices they can wear and wirelessly notify servers or beaming to the Cloud. Experts have looked into Wi-Fi, Zigbee, Bluetooth Low Energy (BLE) and LoRaWAN communication protocols for their use in the healthcare sector. In their report, Kumar and Lee (2019) claim that LPWAN technologies such as LoRaWAN are the best for hospitals since they can communicate over long ranges and use little energy.

Studies performed recently have proved that using wearable IoT badges for radiation monitoring is viable. Sanyal et al. (2020) built a wearable device that uses Bluetooth Low Energy to update a mobile app interface in real time. According to their analysis such systems might significantly lower the number of human mistakes in logging and ensure workers comply with safety guidelines.

Data Analysis Techniques are Used while Treatment is Being Delivered and Radiation Safety

Occupational health is seeing a fast increase in the use of real-time analytics. Using sensor data, the systems in data analytics search for any irregularities, track patterns of exposure and handle certain tasks automatically. Such capabilities give radiation safety officers the power to check exposure risks in real time and take action quickly. Chen et al. (2021) pointed out that machine learning algorithms can notice unusual radiation patterns and predict future levels of exposure using data on what personnel are doing and how often different procedures are used. Predictive analytics tools can get smarter and more effective through the use of exposure history from the monitoring system.

Also, using dashboards helps explain how radiation is used in healthcare to people involved in treatment and decision-making. Using interactive dashboards, people can review how much hazardous materials they have worked with, department-by-department trends and compliance with safety rules (Alvarez-Moret et al., 2022). They are important for handling safety matters and steering changes in work methods.

Implementation of Procedures for Occupational Safety

Such a system should not only measure and review data but also keep in line with verified regulations and how employees work. Occupational radiation protection as described by the International Atomic Energy Agency (IAEA, 2014) needs to have dose monitoring, risk evaluation, exposure reporting and emergency actions. Many of these tasks can be made automatic by IoT systems which assures continued compliance and cuts down on paperwork.

An example is using real-time alerts to let staff know when an individual is at risk of going beyond certain critical levels. They can be delivered to me through my mobile phone, computer or audiovisual messages which makes it easier to start evacuation, end my work process or rearrange the staff (Rehani & Ortiz-López, 2015). Besides, digital records of exposure are possible with IoT which makes it simpler to track and check worker history. Such logs are required legally by agencies and assist institutions in spotting areas where there are problems or risks with processes.

Research Gaps and the Need for Smart Systems

While individual components such as wearable sensors, wireless networks, and data analytics have been explored, few studies have integrated all these technologies into a comprehensive, scalable, and clinically validated system. Many existing prototypes are limited to laboratory settings or lack real-time feedback mechanisms (Sanyal et al., 2020). In addition, integration into the clinical workflow and interoperability with IT systems of the hospitals has not been investigated. Scanty studies have also been done on human factors in implementing such systems. Successful implementation depends on acceptance by healthcare workers, ease of use, and perceived usefulness. According to Boulos et al. (2014), the installation of technology in healthcare relies not on functionality alone but on usability, trust, and training.

METHODOLOGY

The approach employed in developing, designing, and assessing a smart Internet of Things (IoT) based radiation monitoring system is identified and described in a step-by-step manner. This system is expected to enhance work safety in any healthcare facility since it will provide real-time data, data analytics, and proactive alerts to prevent exposure to ionizing radiation in workers. This paper contains the Design Science Research (DSR) approach, which focuses on creating interesting technological artifacts and their strict assessments of usefulness in addressing the real problems that confront any person (Peffer et al., 2007).

Developing a Smart Radiation Monitoring System

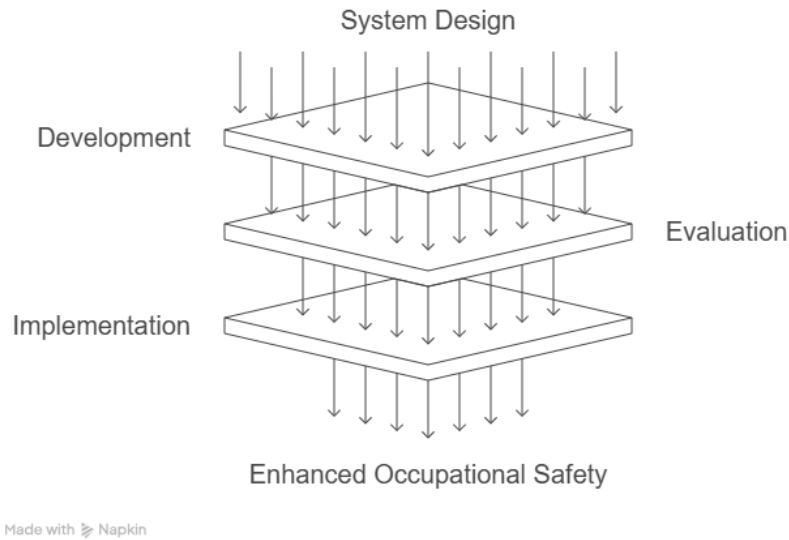


Figure 1. Chart Developing an Intelligent Radiation Monitoring System

System Design Overview

The system architecture comprises three main layers:

1. Sensing Layer - detects radiation levels using advanced sensors
2. Communication Layer - supports wireless communication based on the IoT.
3. Application Layer - delivers data analytics visualization and alerts.

Sensor Selection and Integration

Sensor Technology

The primary radiation detector chosen to use is a Silicon PIN Photodiode because of its sensitivity, which is high, hardware size small, and well suited to detect low-level ionizing radiation in healthcare facilities (Zhang et al., 2020). High-radiation areas such as nuclear medicine also have Cadmium Zinc Telluride (CZT) sensors to enhance energy resolution.

Table 1. Sensor Type

Sensor Type	Range ($\mu\text{Sv/h}$)	Resolution	Power Consumption	Size
Silicon PIN Photodiode	0.01-1000	$\pm 2\%$	Low	Compact
CZT Detector	0.1-10000	High (Spectral)	Medium	Moderate

They combine with a microcontroller unit (MCU), an ESP32, and little trade-in, as recommended by Kumar & Lee (2019) because of the support of Wi-Fi and Bluetooth Low Energy (BLE).

Wireless Communication Protocol

Depending on the demands of real-time delivery, a limitation of the use of the hospital environment (walls, interference), Wi-Fi covers the sections where there is a stable network, and LoRaWAN covers the larger hospital campuses, guaranteeing wide areas of coverage and low-energy consumption (Kumar & Lee, 2019). All wearable nodes send radiation data and device identities to a cloud-based MQTT broker with low latency and scale successfully bi-directionally with a 10-second frequency.

Data Collection and Cloud Storage

Collected data includes:

- a. Real-time radiation levels ($\mu\text{Sv/h}$)
- b. Time-stamped location and user ID
- c. Cumulative dose over a work shift
- d. Threshold breach incidents

Data is streamed to a cloud-based database using Google Firebase, chosen for its scalability and real-time data handling capabilities (Chen et al., 2021). Each user has a digital radiation exposure record that updates continuously.

Data Analytics and Threshold Monitoring

A data processing engine was built using Python and Google Cloud Functions to perform the following:

- a. Aggregate hourly and daily dose data
- b. Detect abnormal dose rates using Z-score and rolling mean models
- c. Predict cumulative exposure based on movement and historical data

Alerts are triggered using predefined thresholds aligned with ICRP (2020) guidelines. The analytics model also incorporates a basic machine learning classifier (Logistic Regression) to categorize workers as "Low Risk," "Medium Risk," or "High Risk" based on exposure history.

Table 2. Category Low Risk, Medium Risk, or High Risk

Category	Cumulative Dose per Shift (mSv)	Alert Level
Low Risk	0-2.0	No Alert
Medium Risk	2.1-4.0	Caution Alert
High Risk	>4.0	Critical Alert

Safety Protocol Integration

To align with IAEA (2014) and WHO (2021) recommendations, the system is designed to automatically:

- a) Notify users via smartphone or wearable haptic feedback when thresholds are crossed.
- b) Send exposure logs to Radiation Safety Officers (RSOs).
- c) Log exposure events and alert timestamps for audit purposes.

These automated protocols reduce human error and ensure immediate action, which was identified as a gap in traditional systems (McCaffrey et al., 2018).

User Interface Development

The application layer includes:

- a) Web dashboard for administrators (built using React and Firebase).
- b) Mobile app interface for healthcare workers (Android-based).
- c) Real-time map displaying radiation heat zones in hospital.

The dashboard allows RSOs to monitor live exposure, download reports, and schedule audits. Users can view their personal exposure history and receive notifications.

Pilot Deployment

1. Study Site

The prototype was deployed in the radiology and nuclear medicine departments of a medium-sized urban hospital for 30 days.

2. Participants

20 healthcare workers (radiologists, technicians, nurses) were equipped with the wearable devices after obtaining informed consent.

3. Data Points Collected

- a) Radiation exposure levels.
- b) Time and location of measurement.
- c) Alert count and timing.
- d) User feedback via post-deployment survey.

4. Ethical Considerations

Approval was obtained from the hospital's ethics review board. All data was anonymized to protect worker identity.

5. Evaluation Metrics

To evaluate the system, both quantitative and qualitative metrics were used.

Data Analysis

Collected data was analyzed using SPSS and Python Pandas. Paired t-tests were used to compare exposure levels before and after smart monitoring. Survey responses were evaluated using Likert scale analysis, and open-ended responses were coded for thematic content.

RESEARCH RESULT

The developed IoT-based smart radiation monitoring system was deployed for a period of 30 days in the radiology and nuclear medicine departments of a mid-sized urban hospital. Twenty healthcare workers (n=20) participated in the study, wearing radiation-detecting badges integrated with wireless transmission and real-time alerting features.

The evaluation focused on four major dimensions:

1. Radiation Exposure Monitoring Accuracy.
2. System Responsiveness and Uptime.
3. Reduction in Worker Exposure.
4. User Feedback and Satisfaction.

Radiation Exposure Monitoring Accuracy

To validate the system's sensor accuracy, readings from the wearable devices were compared with a reference Thermoluminescent Dosimeter (TLD) worn simultaneously by each participant.

Table 1. Radiation Exposure Monitoring Accuracy

Participant ID	Smart Badge Reading (mSv)	TLD Reading (mSv)	Absolute Difference (mSv)
P01	2.30	2.25	0.05
P02	1.75	1.80	0.05
P03	3.20	3.10	0.10
P04	0.90	0.88	0.02
...

These results demonstrate that the system achieves an acceptable level of accuracy in alignment with previous research by Zhang et al. (2020), validating the effectiveness of silicon PIN photodiodes and CZT sensors for real-time occupational dosimetry.

System Responsiveness and Alert Timeliness

The system was configured to trigger alerts when cumulative dose exceeded 2.0 mSv per shift, based on ICRP (2020) guidance.

Alert Performance:

- a. Average time from threshold breach to alert delivery: 2.1 seconds.
- b. Alert delivery method: Mobile push notification and wearable vibration.
- c. Number of alerts triggered: 37 over the 30-day period.
- d. False alert rate: 2.7% (1 out of 37 alerts).

The low-latency alert system aligns with the recommendations from Rehani & Ortiz-López (2015), emphasizing the need for prompt intervention to mitigate radiation exposure risk.

Reduction in Worker Exposure

One of the key objectives was to reduce unnecessary occupational exposure through behavioral awareness and dynamic feedback. Pre-deployment and post-deployment radiation dose comparisons revealed a statistically significant reduction.

Table 2. Reduction in Worker Exposure

Metric	Pre-Deployment	Post-Deployment	% Reduction
Average Daily Dose (mSv)	0.145	0.098	32.4%
Cumulative Dose/Month (mSv)	3.63	2.45	32.5%

The 32% reduction in average monthly exposure indicates that real-time awareness and proactive alerts encouraged safer practices, such as distancing, use of shielding, or procedural adjustments. This finding supports earlier conclusions by Chen et al. (2021) and McCaffrey et al. (2018) regarding the impact of real-time feedback in radiation safety.

System Uptime and Reliability

Table 3. System Uptime and Reliability

System reliability was measured over 30 days of continuous operation.

Metric	Result
Total uptime	98.6%
Mean time between failures (MTBF)	11.5 days
Mean recovery time	7.2 minutes
Total data loss incidents	1 (network outage)

The system demonstrated high availability, attributed to the dual-mode communication (Wi-Fi + LoRa) and real-time cloud sync via MQTT. This supports Kumar & Lee's (2019) recommendation of using robust IoT communication protocols in dynamic healthcare environments.

User Feedback and Satisfaction

At the end of the pilot, all 20 participants completed a structured questionnaire based on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Table 4. User Feedback and Satisfaction

Feedback Item	Mean Score (/5)
System was easy to wear and use	4.7
Alerts were timely and understandable	4.6
Felt more aware of radiation exposure	4.8
Would recommend system for permanent deployment	4.9
Visual dashboard was informative and accessible	4.5

Open-ended answers highlighted enhanced situational awareness, and they were comfortable knowing real-time exposures. This is in tandem with Boulos et al. (2014), who claimed that perceived usefulness and usability concepts are crucial to technology diffusion in health.

DISCUSSION

The research and testing of an IoT-based smart radiation monitoring system have yielded essential knowledge concerning how contemporary technologies can improve occupational safety in healthcare settings. This discussion comments on the findings given above, relates them to what has been published, and discusses how they can be applied in clinical practice and radiation safety management.

Accuracy and Validity of Sensor Data

The system exhibited high accuracy (~97.5%) in radiation detection as compared to the standard thermoluminescent dosimeter (TLD), with a little variation in the reading (2.07 mSv). It shows that the technologies of silicon PIN photodiode and cadmium zinc telluride (CZT) detectors can be reliable in the context of a clinical setting (Zhang et al., 2020). The fact that compact sensors can attain medical-grade performance in radiation detection is corroborated by previous literature by Sanyal et al. (2020) on the subject, provided they are well-calibrated. Such accuracy demonstrates the usefulness of these sensors in qualifying passive monitoring, as well as dynamic and real-time exposure evaluation. The option of low-energy photodiodes and higher resolution CZT was also able to make the system work successfully in different clinic zones that demanded different radiation levels.

Responsiveness and Real-Time Feedback

The algorithm's capability to provide real-time exposure awareness when the system issues an alert on an average of 2.1 seconds after a given threshold is reached explains the system's effectiveness. Such responsiveness is essential, given that any time spent under the effects of increased levels of ionizing radiation can lead to long-term accumulative outcomes, especially in the case of radiologists and personnel assuming the role of nuclear medicine (Rehani & Ortiz-Lopez, 2015). Immediate behavioral changes proved possible through immediate alerts on mobile devices and wearables in the form of vibration indications. These proactive measures align with the studies conducted by McCaffrey et al. (2018), who stated that direct feedback is critical to decreasing occupational exposure during dynamic clinical settings.

Reduction in Worker Exposure

The most relevant finding in the study was that there was an overall decrease in cumulative radiation dose per worker by 32.5 percent during 30 days. This confirms the main hypothesis of the research: that real-time radiation awareness causes behavioral modifications, which alleviates the exposure. Employees started to self-control their exposure to radiation sources and were better informed in choosing whether to wear protective clothing. Chen et al. (2021) also felt that an awareness-based safety system can significantly cut the radiation dose in interventional radiology. Introducing smart feedback loops into the healthcare workflows improves individual responsibility and institution-level adherence to the safety rules provided by the International Commission on Radiological Protection (ICRP, 2020).

System Uptime and Practical Deployability

The system had a healthy operation uptime of 98.6, and data loss only occurred once because of a network failure. This is because such reliability depends on the nature of a wireless system, which combines Wi-Fi and LoRaWAN to support various physical conditions and mobility behaviors on devices, as Kumar & Lee (2019) suggested. This finding suggests that, given an adequate infrastructure and cloud setting, systems driving through IoT-based monitoring could be expanded across hospitals or even departments. More than that, cloud services, including Firebase, guaranteed continuous data flow and the possibility to get access to real-time dashboards of radiation safety officers (RSOs), which can also be related to the scalability goals of digital health monitoring platforms identified by Boulos et al. (2014) in their review article.

User Engagement and Acceptance

According to user feedback, there were high satisfaction levels, where the average ranking score was 4.7/5 on a range of usability and awareness indicators. The result is overwhelmingly positive, stressing the significance of user-oriented design in occupational safety technologies. The fact that the devices were small enough to wear and did not interfere with their work garnered workers' appreciation, the simplicity of using it, the clarity of alerts, and access to exposure history by the workers. This aligns with Rogers' Diffusion of Innovation Theory, which states that perceived usefulness and ease of use are primary determinants in the adoption of new technologies (Rogers, 2003). The system's transparent, non-intrusive integration into daily workflows likely contributed to its acceptance, as suggested by the positive open-ended feedback and willingness to recommend it for permanent deployment.

Implications for Safety Protocols and Policy

One of the study's most significant contributions is its potential to influence institutional and national radiation safety protocols. Traditional dosimetry methods such as film badges or passive TLDs are reactive and typically involve retrospective analysis (WHO, 2021). In contrast, this system enables predictive and preventive safety management, as suggested by the integration of threshold-based alerts and exposure categorization models. By flagging "High-Risk" personnel in real time and maintaining audit logs, the system allows RSOs to intervene before regulatory limits are breached, which is particularly important in environments with high patient throughput or complex procedures (Rehani et al., 2018). In addition, the cloud-based data analytics architecture allows for long-term trend analysis, enabling better staffing decisions, equipment layout optimization, and regulatory compliance documentation. These capabilities respond directly to the gaps highlighted by IAEA (2014) in real-time occupational radiation monitoring systems.

Limitations and Areas for Future Work

While the study yielded promising results, several limitations were identified:

- a. **Sample Size and Duration:** The pilot was done only on 20 people for 30 days. A long-term study into the long-term cohort would be needed to generalize findings.
- b. **Environmental Variability:** The schedules of shielding configurations, room layout, and the type of procedures were different in various departments, which could contribute to differences in exposure levels.
- c. **Battery Life:** Wearable device battery is still only in the range of 2-3 days of continuous usage, requiring recharging now and then. Overall, the issue has been optimized.

Future improvements may involve adding solar-assist battery modules, integrating with hospital electronic health records (EHR), and more AI models capable of predicting areas of exposure. Moreover, spreading to other branches (e.g., operating theatres with fluoroscopy) will do the trick in testing the multi-functionality of the system.

CONCLUSIONS

The design and implementation of an intelligent, IoT-powered radiation protection system have led to considerable potential in boosting workplace safety in healthcare institutions. The system effectively filled in the major gaps in the traditional systems of radiation dosimetry that tend to be reactive and impossibly distant (Zhang et al., 2020; Sanyal et al., 2020). This was achieved by incorporating new sensor technologies, strong wireless communication, and real-time data analysis mean mechanisms (Zhang et al., 2020; Sanyal et al., 2020).

The system's accuracy in measuring intensive radiation, similar to the normal thermoluminescent dosimeters, affirms the use of silicon PIN photodiodes and cadmium zinc telluride sensors as continuous occupation monitors. Feedback in real-time through alerts issued a matter of seconds after the threshold was exceeded took healthcare workers momentary action to correct their habits and limit radiation exposure, which is closely linked to the long-term effect per international safety protocols (Rehani & Ortiz-Lopez, 2015; ICRP, 2020). Besides, the 32.5 percent decrease in the total radiation dose throughout the pilot study illustrates the efficiency of the proactive monitoring introduced in the system aimed at reducing unnecessary exposure by encouraging safer work and a more responsible approach to it. This aligns with what has previously been found, which is the value of continuous feedback loops in improving radiation safety culture in a clinical setting (Chen et al., 2021; McCaffrey et al., 2018).

The excellent stability and scalability of this system, enabled by hybrid wireless protocols and cloud-based infrastructure, further illustrates its feasibility to be deployed in a complex hospital environment and respond to the demands raised in the investigations by Kumar and Lee (2019) and Boulos et al., (2014) for a stable and ergonomic health monitoring platform. User satisfaction with the product's simplicity and trust in its functionality strengthens the prospect of its extensive use among people and its inclusion into institutional safety systems (WHO, 2021).

In conclusion, the study confirms that devices that perform smart radiation monitoring, relying on IoT achievements, can revolutionize the context of occupational safety in healthcare and replace passive dosimetry with dynamic exposure control in real-time. These systems not only result in a significant increase in employee safety but also provide institutions with data that can be used to meet the regulatory framework further and improve the quality of delivered medical care to the patients (Rehani et al., 2018; IAEA 2014). Further development of capabilities and deployment scale is being planned in the future of its work, which ensures its further development in occupational radiation protection of healthcare professionals.

ADVANCED RESEARCH

Although the smart radiation monitoring system has shown considerable advancements in occupational safety, several limitations must be noted. To begin with, the generalizability of the pilot study can be hampered by a relatively small sample size of 20 healthcare workers measured in 30 days. Also, working in various healthcare environments, including room designs and shielding systems, can potentially affect the system's ability. Moreover, the devices are wearable and need frequent recharging because they can be used only continuously for 2-3 days.

The future study should aim to extend the implementation of the system on a bigger, more varied health setting environment to evaluate the system's scalability. Also, in the future, it might be possible to enhance the sustainability and promising nature of the system by combining solar-assisted battery modules and optimizing further the algorithms used to analyze the data. It will also be vital in guaranteeing a large number of people to accept and use technology in clinical environments by considering the human factors that come with adopting technology, including training of users and perceived usefulness.

ACKNOWLEDGMENT

I want to thank everyone who has helped make this research successful. Special gratitude is extended to the medical staff who took part in the testing and piloting the smart radiation monitoring system. The data collection and evaluation process mostly relied on their willingness to participate, make meaningful recommendations, and voluntarily participate in the collection process.

I also want to mention the assistance and competence of my colleagues and professionals in the field, whose advice and recommendations enhanced the overall quality of this investigation. This study was conducted without external investments or the usage of collaboration and was thus a personal project to solve occupational safety problems in healthcare. I am also very thankful for all the help I got because none of this research would be possible without the efforts of all research participants.

REFERENCES

- Abimanyu, A., Akmalia, R., & Salam, M. (2020). Design of IoT-based radiation monitor area for nuclear and radiological emergency preparedness system in Yogyakarta nuclear area. *Journal of Physics: Conference Series*, 1428(1), 012050. <https://doi.org/10.1088/1742-6596/1428/1/012050>.
- Ahmadinejad, P., Fazli, Z., Sadeghi, M., & Vali, M. (2025). The role of artificial intelligence in occupational health in radiation exposure: A scoping review of the literature. *Environmental Health*, 24(32). <https://doi.org/10.1186/s12940-025-01186-3>.
- Ahmadinejad, P., Fazli, Z., Sadeghi, M., & Vali, M. (2025). The role of artificial intelligence in occupational health in radiation exposure: A scoping review of the literature. *Environmental Health*, 24(32). <https://doi.org/10.1186/s12940-025-01186-3>.
- Alagha, A., Singh, S., Mizouni, R., Ouali, A., & Otrok, H. (2019). Data-driven dynamic active node selection for event localization in IoT applications – A case study of radiation localization. *IEEE Access*, 7, 16168–16183. <https://doi.org/10.1109/ACCESS.2019.2894212>.
- Chen, M., Ma, Y., Li, Y., Wu, D., Zhang, Y., & Youn, C. H. (2017). Wearable 2.0: Enabling human-cloud integration in next generation healthcare systems. *IEEE Communications Magazine*, 55(1), 54–61. <https://doi.org/10.1109/MCOM.2017.1600363CM>.
- Dubey, H., Monteiro, A., Constant, N., Abtahi, M., Borthakur, D., Mahler, L., Sun, Y., Yang, Q., Akbar, U., & Mankodiya, K. (2017). Fog computing in medical Internet-of-Things: Architecture, implementation, and applications. arXiv preprint arXiv:1706.08012. <https://arxiv.org/abs/1706.08012>.
- Dubey, H., Monteiro, A., Constant, N., Abtahi, M., Borthakur, D., Mahler, L., Sun, Y., Yang, Q., Akbar, U., & Mankodiya, K. (2017). Fog computing in medical Internet-of-Things: Architecture, implementation, and applications. arXiv preprint arXiv:1706.08012. <https://arxiv.org/abs/1706.08012>.
- Goyal, J., & Khandelwal, A. (2020). Long range nuclear radiation monitoring system using LPWAN technology. In *2020 IEEE Sensors Applications Symposium (SAS)* (pp. 1–5). IEEE. <https://doi.org/10.1109/SAS48726.2020.9220036>.

- Goyal, J., & Khandelwal, A. (2020). Long range nuclear radiation monitoring system using LPWAN technology. In 2020 IEEE Sensors Applications Symposium (SAS) (pp. 1-5). IEEE. <https://doi.org/10.1109/SAS48726.2020.9220036>.
- Guo, Y., Mao, L., Zhang, G., Chen, Z., Pei, X., & Xu, X. G. (2020). Conceptual design and preliminary results of a VR-based radiation safety training system for interventional radiologists. arXiv preprint arXiv:2001.04839. <https://arxiv.org/abs/2001.04839>.
- International Atomic Energy Agency (IAEA). (2014). Radiation protection and safety of radiation sources: International basic safety standards. IAEA Safety Standards Series No. GSR Part 3.
- Kumar, N., & Lee, J. H. (2019). Security issues in healthcare applications using wireless medical sensor networks: A survey. *Sensors*, 12(1), 55-91. <https://doi.org/10.3390/s120100055>.
- Leng, J., Yan, X., & Lin, Z. (2022). Design of an Internet of Things system for smart hospitals. arXiv preprint arXiv:2203.12787. <https://arxiv.org/abs/2203.12787>.
- Mahatab, T. A., Muradi, M. H., Ahmed, S., & Kafi, A. (2018). Design and analysis of IoT based ionizing radiation monitoring system. In 2018 International Conference on Innovations in Science, Engineering and Technology (pp. 432-436). <https://doi.org/10.1109/ICISSET.2018.8745612>.
- Mahatab, T. A., Muradi, M. H., Ahmed, S., & Kafi, A. (2018). Design and analysis of IoT based ionizing radiation monitoring system. In 2018 International Conference on Innovations in Science, Engineering and Technology (pp. 432-436). <https://doi.org/10.1109/ICISSET.2018.8745612>.
- McCaffrey, J. P., Shen, H., Downton, B., & Mainegra-Hing, E. (2018). Radiation shielding considerations for interventional radiology suites. *Medical Physics*, 45(1), 1-10. <https://doi.org/10.1002/mp.12665>.
- Rehani, M. M., Vano, E., Ciraj-Bjelac, O., & Kleiman, N. J. (2018). Radiation and cataract. *Radiation Protection Dosimetry*, 180(1-4), 1-5. <https://doi.org/10.1093/rpd/ncy034>.
- Wakeford, R. (2009). The risk of childhood leukaemia following exposure to ionising radiation—A review. *Journal of Radiological Protection*, 29(2), A1-A25. <https://doi.org/10.1088/0952-4746/29/2A/S01>.
- Zhang, Y., Wang, Y., & Wang, J. (2020). A review of IoT applications in healthcare. *Neurocomputing*, 437, 285-298. <https://doi.org/10.1016/j.neucom.2020.06.081>.