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IoT-Based Real-Time Radiation Monitoring System for Cardiac Catheterization Rooms

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ABSTRACT

Cardiac catheterization is a significant exposure risk for healthcare workers to ionizing radiation. Repeated low doses may increase the lifetime risk of cancer, so it is important to monitor doses in real-time to minimize unnecessary exposure and to safeguard workers. Traditional personal dosimeters provide limited feedback and delayed readings. In this paper, a low-cost Internet of Things (IoT)-based system that enables real-time radiation monitoring to support occupational safety is presented. The system uses an SBM-20 Geiger-Müller tube connected to an ESP32 microcontroller to count pulses in counts per minute (CPM) and calculate the dose rate and cumulative dose. Data are transmitted via local Wi-Fi using HTTP/JSON to a local Flask-based server, stored in an stores it in a database (SQLite), and displayed through an interactive web dashboard with real-time alerts. The system was field-tested in a catheterization laboratory for four weeks. For detailed analysis, the day with the highest number of procedures was selected as a case study, during which nine interventional procedures were performed by a single physician. The average background radiation in the hospital was approximately 22 CPM (0.17 μSv/h). The average cumulative dose per procedure was 1.54 ± 1.00 μSv. The dose rate ranged from 5.09 to 15.98 μSv/h, with an overall average of 7.88 μSv/h.

1. INTRODUCTION

The cardiac catheterization lab is one of the most radiation-exposed medical environments, where scattered X-rays are generated inside the operating room [1]. Long-term occupational exposure to radiation may increase the risk of developing serious cancers. Even if radiation doses are small, repeated exposure over time may pose a risk to human health [2, 3]. Ionizing radiation is energy emitted from a radiation source in the form of electromagnetic waves or particles capable of causing ionization within matter, including alpha, beta, gamma, and X-ray radiation. Types of radiation vary in terms of their penetrating power and the protection measures required. Alpha radiation has low penetrating power but can be dangerous if inhaled or ingested. Beta radiation has medium penetrating power, while gamma and X-ray radiation have high penetrating power and require appropriate safety precautions in terms of exposure time, distance from the radiation source, and shielding to reduce the effects of radiation [4]. The average annual dose of natural background radiation is approximately (2.4 mSv/year), according to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [5]. International standards have also established occupational dose limits for radiation workers, which are set at an average of (20 mSv/year) and should not exceed (50 mSv/year) in a single year [6, 7]. The International Commission on Radiological Protection (ICRP) recommends a maximum occupational dose of 20 mSv/year averaged over a period of time. For contextual comparison, the annual limit was 365 days, corresponding to 54.8 μSv/day per calendar day. This value is provided only for reference and is not intended to represent a daily occupational dose limit. Nevertheless, traditional methods used to measure radiation levels face several challenges, including accessing data in real time, which may negatively affect radiation and increase the risk of radiation exposure. The catheterization laboratory is one of the environments where healthcare personnel are exposed to radiation due to their proximity to the radiation source. The increasing number of interventional catheterization procedures in recent years may result in increased cumulative occupational doses, making real-time monitoring of healthcare personnel necessary to reduce the risk of radiation exposure [8, 9]. Although safety measures, such as using protective shields and minimizing exposure time whenever possible, are followed, real-time monitoring and cumulative dose recording remain major challenges. Addressing these challenges can play an important role in supporting preventive measures during work, particularly when monitoring is performed automatically. Many Healthcare institutions still rely on traditional methods of measuring occupational exposure, such as film badges or thermoluminescent dosimeters (TLDs), that are read periodically, resulting in delayed feedback and limiting immediate preventive decisions during the procedure. This delay may reduce the effectiveness of the preventive response and increase the likelihood of exceeding thresholds or accumulating without immediate attention [10, 11]. Therefore, these limitations motivate the use of Internet of Things (IoT) in this field [12].

Radiation exposure monitoring also applies to interventional radiology suites, nuclear medicine departments, and radiation therapy clinics where personnel experience comparable chronic low-dose exposures. Deployment of IoT-based monitoring in these environments bridges the areas of occupational health, medical IoT, and preventive health–a cross-cutting area explored in this paper.

IoT can be defined as a system that connects devices, nodes, or sensors to networks for the purpose of controlling devices remotely, collecting data automatically, decision-making, or even just monitoring. IoT system operates in layers, starting from the nodes and ending with servers for data processing. These servers can be local or cloud-based, depending on system requirements in terms of real-time, capacity, security, and cost [13, 14].

The use of IoT applications in the health sector is important because it enables real-time monitoring and analysis and the continuous collection of measurements over long periods of time, which improves service data management and analysis [15].

The communication technologies used within IoT systems are diverse and are selected according to the required range, data rate, and volume, for example:

•Short/medium range such as Wi-Fi, Bluetooth, ZigBee, NFC [16].

•Low-power wide-area networks (LPWAN) such as NB-IoT, LoRa/LoRaWAN, and LTE-M, which are suitable for covering large areas and require low power consumption [17].

•Cellular communication includes LTE/4G and 5G and falls within the scope of wide-area networks [18].

The most appropriate technology is selected based on the environment and operational constraints specified by the relevant healthcare institution [19].

1.1 Research gap and motivation

This paper addresses the gap between delayed measurement and traditional periodic radiation dose metrics and the need for practical, low-cost, real-time professional monitoring that maintains privacy within the catheterization laboratory and proposes a local system for real-time radiation monitoring for professional staff inside the catheterization laboratory. The system relies on a Geiger-Müller sensor to capture radiation pulses and convert them into displayable indicators, which are then sent via a local network to a Flask-based backend server for storage, analysis, dose rate calculation, cumulative dose calculation (daily/weekly), limit checking, and alert triggering, with an interactive web panel for displaying readings and exposure history, supporting preventive decision-making within the hospital environment.

1.2 Contributions of the study

•Design a low-cost measurement system that can be used inside the catheterization room to measure radiation in real time.

•Develop a local backend architecture to store readings and track cumulative dose without relying on external cloud services.

•Integrate occupational safety limit checks and real-time alerts into an interactive web dashboard.

•Provide a practical application framework that meets hospital requirements for privacy, reliability, and ease of use.

Distinct from prior works that utilize commercial dosimeters, cloud-based architectures, or periodic TLD scanning, this work provides an entirely local, low-cost IoT system architecture that uses open-source hardware and software, with integrated real-time counts per minute (CPM)-to-dose conversion and session-linked cumulative dose tracking along with an interactive web-based dashboard, designed specifically for the operational realities and privacy requirements of cardiac catheterization labs and functions entirely independent of external networks or vendor-specific hardware.

2. RELATED WORKS

Recently, IoT has been used to measure radiation, store and analyze data in real time, and trigger alerts. Chowdhury et al. [20] proposed the Smart Geiger system as a low-cost model based on an ESP32 microcontroller and the MicroPython programming language with a Node-RED interface and MQTT protocol to upload data and display readings in real time, demonstrating the feasibility of building radiation monitoring systems based on IoT using simple hardware. A key limitation is that the system focuses more on general architecture than on being specialized for catheterization rooms and occupational safety requirements. On the other hand, Saifullah et al. [21] proposed an AI system that predicted the levels of radiation in real-time and provided warnings accordingly. Different algorithms were used in this work; the best accuracy was achieved by the AdaBoost algorithm (81.77%). In terms of cost, Le et al. [22] proposed a low-cost system for displaying radiation measurements based on open-source platforms that help monitor and display data. Saleem et al. [23] also proposed an intelligent system based on the Waspmote platform for real-time radiation detection. They used AES-256 encryption to protect data before sending it through 3G networks and storing it in cloud computing. In another context, Holt [24] proposed a smart system for radiation monitoring and improved occupational safety in the healthcare environment using Geiger-Müller sensors with semiconductive sensors, Wi-Fi and LoRaWAN networks, and machine learning algorithms to analyze data, predict abnormal exposure situations, and trigger alerts. A 32.5% reduction in worker exposure and an improvement in occupational safety were observed.

On the other hand, Murat et al. [25] presented a study that explained the importance of real-time radiation measurements and alert devices. This study showed a 60% reduction in exposure hazards in cardiac catheterization labs. This reduction was attributed to changes in staff behavior in response to real-time exposure alerts. Vano et al. [26] proposed a system to improve staff protection in interventional radiology by using electronic dosimeters wirelessly connected to a dose management system (DMS) to measure staff dose for each procedure and link it to patient dose indicators and procedure conditions. They also proposed an alert mechanism based on the personal dose value for each procedure and the ratio of the personal dose to the reference environmental dose near the radiation source to detect cases of poor compliance with protection. Despite its effectiveness, the approach relies on commercial electronic devices and a ready-made DMS does not offer a low-cost design based on IoT, a local server and a web dashboard dedicated to the cardiac catheterization room. Jeong et al. [27] designed a real-time personnel radiation dosimeter that integrated a scintillator with a thin-film solar cell, providing a low-cost, portable and accurate radiation monitoring device for fluoroscopic procedures. Salvi et al. [28] presented an innovative personal electronic dosimeter that could detect and measure both gamma and beta radiation with the help of a scintillator and SiPM sensor, the validation being performed with experimental results and the results being compared with Monte Carlo simulations. Parikh et al. [29] proposed an in-lab catheterization protection system consisting of solid shields and radiation-resistant covers around the table to reduce scattered radiation to the entire catheterization team. A comparison was made on 50 diagnostic catheterization cases using instantaneous dosimeters, and the results showed a significant reduction in head-level doses for the physician, technician, and nurse with this system without increasing the patient's dose. While the protection system has significantly reduced the radiation dose to which staff is exposed, it focuses on physical protection and commercial dosimeters rather than a low-cost IoT-based monitoring and alert platform. In another context, Ageel [30] studied occupational radiation exposure among anesthesia staff in cardiac catheterization laboratories by assessing skin dose Hp (0.07) using TLDs over a five-year period (2019-2023), providing a reference value for annual exposure and comparisons by job title and gender, emphasizing the ALARA principle and the need for training and protective equipment. However, this approach relied on periodic (quarterly) measurements, did not provide real-time monitoring or immediate alerts during the procedure, and did not offer a local IoT platform for real-time data storage, visualization, and alerts. Madder et al. [31] showed that rare high-dose cases in the catheterization laboratory contributed disproportionately to cumulative occupational dose, with the highest 10% of cases accounting for approximately 60% of a cumulative dose, while the lowest half of cases contributed very little. The study relied on measuring staff dose for each procedure using instantaneous dosimeters Hp (10) and showed that relying on the median dose for each case may not reflect the true cumulative risk. It also identified characteristics of procedures associated with an increased likelihood of falling into the high-dose category (such as STEMI, PCI, and RHC). However, this work remained analytical and relied on a commercial dosimeter system without providing a low-cost IoT platform for local data storage, web dashboard, real-time alerts, and individual tracking of cumulative dose.

Regarding the use of local networks and their advantages over cloud services, Andriulo et al. [32] presented a systematic review comparing cloud computing, edge computing, and hybrid architectures (such as fog/mist) within IoT systems, showing that edge computing reduces latency and improves privacy through local processing, while cloud computing offers greater scalability and flexibility. It also concluded that hybrid architectures represent a balanced option for privacy-sensitive real-time applications, as they reduce network load and latency while leveraging the cloud's capabilities for heavy tasks. However, this paper remained a general review and does not provide a specialized application for radiation monitoring and occupational safety in catheterization rooms (such as cumulative dose calculation and alerts). Elhadad et al. [33] presented a healthcare monitoring framework that integrated IoT with fog computing to manage real-time notifications and reduce delays by processing data close to its source before uploading it to cloud computing. The proposed architecture relied on collecting data from medical sensors and then analyzing it in the fog layer to make rapid decisions and send immediate alerts, while using cloud computing for storage and long-term analysis. However, this work remains general for health monitoring and does not address occupational radiation monitoring within catheterization rooms or cumulative dose calculation and safety alerts according to occupational thresholds within a low-cost local platform.

Therefore, this paper focuses on presenting a solution that combines real-time monitoring within the hospital environment via a local server, with cumulative dose management, instant alerts, and a dedicated visualization panel for the cardiac catheterization room.

Radiation level measurement has improved in the surveyed systems, but they also present drawbacks. Systems with cloud dependencies [23, 33] suffer from latency issues and privacy limitations that make them unacceptable for clinical use. Solutions based on commercial dosimeters [26, 29, 31] lack transparency and have no open-source SDKs due to their cost. Although AI-based systems perform better at prediction [21, 24], they require resources for computational power and datasets for training. To our knowledge, no work has addressed local server-based recordings of radiation levels while keeping track of per-session cumulative dose, sending real-time alerts to a web interface, and operating on low-cost hardware designed specifically for use in a catheterization room.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

3.1 Overall system architecture

The proposed system is a local IoT system designed to monitor ionizing radiation in cardiac catheterization labs. The system comprises four layers:

•Sensor layer;
•Edge-Node layer;
•Backend layer;
•User interface layer.

Figure 1 shows the architecture of the proposed system.

The SBM-20 Geiger-Müller tube in the sensor layer detects the ionizing particles and outputs electrical pulses. The ESP32 receives these pulses, processes and converts them into digital values, and sends them through a local wireless network to the backend server built on Flask. Then, they are processed for display on the user interface. The purpose of using a local wireless network is to reduce the time delay that happens when relying on cloud servers.

The system architecture was designed based on the requirements of the cardiac catheterization laboratory, the most important of which are reducing the response time to alerts, ensuring local operation within the hospital network without relying on cloud services, and continuously recording the cumulative dose for staff. Accordingly, a local server was adopted to process and store data and manage alerts, while measurements were periodically sent from the node to the server via the local Wi-Fi network. If the Wi-Fi connection is lost, the ESP32 will try to reconnect automatically and the data transmission resumes once the connection is restored, when the next measurement event arrives. Low-cost and easy-to-maintain solutions were also chosen to ensure the applicability of the system in clinical environments with limited resources.

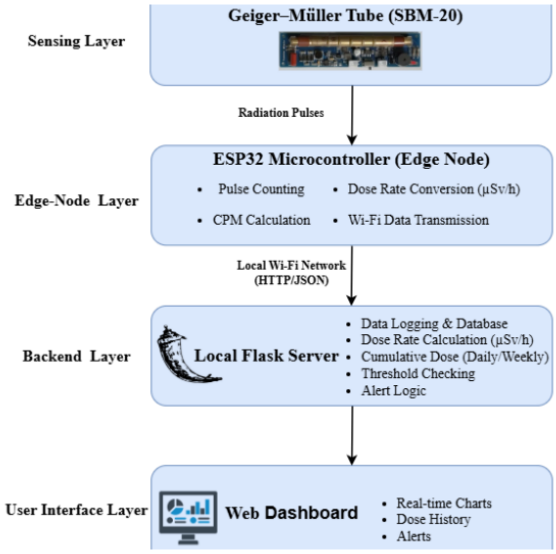


Figure 1. System architecture

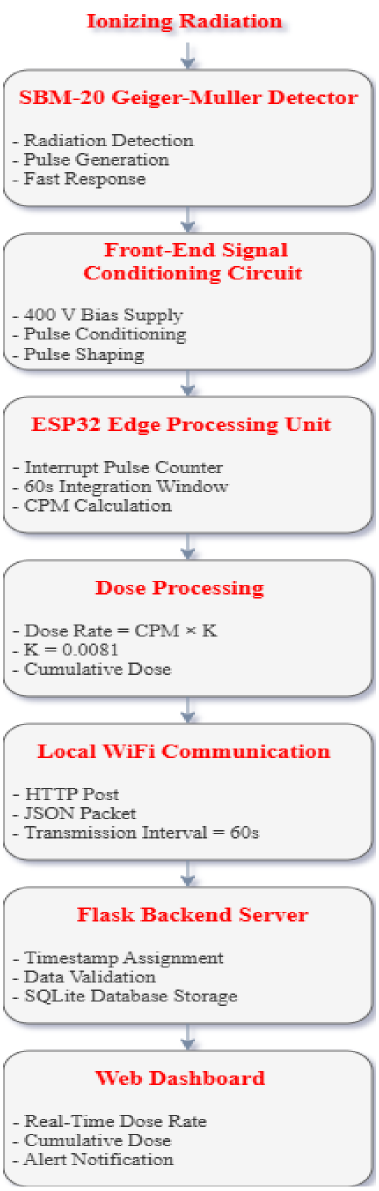


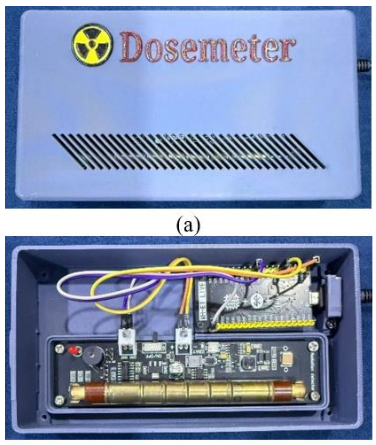
Figure 2. The proposed Internet of Things (IoT)-based radiation monitoring system's measurement chain

For greater clarity of the proposed measurement process, Figure 2 shows the entire measurement chain of the developed radiation monitoring system, ranging from radiation detection by the SBM-20 Geiger-Müller detector to signal conditioning, pulse counting, dose calculation, wireless communication, backend processing and real-time visualization of the results.

The SBM-20 Geiger-Müller detector detects the radiation first and generates electrical pulses that are proportional to the intensity of the radiation, as shown in Figure 2. The front-end signal conditioning circuit conditions the pulses before sending them to the ESP32 edge processing unit for pulse counting, which is done over a 60 s integration period and the CPM is calculated. The measured CPM is then multiplied by the chosen conversion factor to get the dose rate or cumulative dose. Processed data are sent to the Flask backend server every 60 s through HTTP/JSON over the local Wi-Fi network, which assigns a timestamp, validates the data, writes the data to the SQLite database and displays it on the web dashboard for real-time monitoring and alert notification.

3.2 Hardware design

The radiation dosimeter is shown in Figure 3, where subfigure (a) represents the external shape of the device and subfigure (b) shows the internal components.



(a)

(b)

Figure 3. The implemented system: (a) external shape and (b) internal components

3.2.1 Geiger-Müller tube (SBM-20)

The SBM-20 is a high-sensitivity radiation sensor used to detect ionizing radiation, making it suitable for use in hospital environments. It produces electrical pulses at a rate that is proportional to the intensity of the radiation. The SBM-20 tube operates within a voltage range of 350 to 475 V, with a nominal operating voltage of approximately 400 V. Its effective length is 108 mm. Sensitivity to Cs-137 gamma rays is approximately 44 counts per second (CPS) per mR/h with a readable range from background to about 1000 μSv/h before saturation. The SBM-20 detector was employed in the present study for the detection of scattered occupational radiation instead of a direct X-ray beam. The dose rates that were measured throughout all cardiac catheterization procedures were below the detector saturation limit of (~1000 μSv/h). Thus, during the experiments, the detector was never saturated and is not expected to have caused any errors in the measurement. Sources of measurement uncertainty are tube dead time (~190 μs), temperature-sensitive voltage drift and background contribution from cosmic rays, as seen with all Geiger-type designs; however, these are acceptable for monitoring purposes.

3.2.2 ESP32 microcontroller unit

The ESP32 is a low-power wireless communication microcontroller that sends and receives data in real-time. It counts the pulses received from the SBM-20, converts the pulses to digital values, and sends them through Wi-Fi.

3.2.3 Power supply

The system includes a suitable power bank that ensures stable operation by providing a continuous 5 V direct current (DC) supply.

3.2.4 3D-printed enclosure

A special enclosure was designed and printed using 3D printing technology to protect the electronic components, improve the ease of handling the device, and ensure its suitability for use in the cardiac catheterization laboratory with the following dimensions (14.5 cm × 8 cm × 3.5 cm).

3.3 Software design and implementation

The proposed system is based on ESP32 programming, a local wireless network communication protocol, a Flask-based backend server, a local SQLite database, and an interactive web dashboard for displaying readings, exposure history, and alerts. Locally calculated indicators are sent to the backend server for storage and analysis, calculation of dose rate and cumulative dose (daily/weekly), limit verification, and triggering of alerts. The ESP32 module calculates the pulses sent from the SBM-20 Geiger-Müller tube and converts them into processable digital values. To ensure reading stability and eliminate random hits, the pulses are aggregated within a fixed time, and then the number of pulses CPM is calculated. The 60-second interval was selected to enhance the counting statistics and minimize random fluctuations typically found in low-counting-rate Geiger-Müller measurements in background and occupational exposure situations. Faster updates with a shorter integration time would be possible (e.g., 10 s or 30 s), but the statistical uncertainty of the measurement would increase considerably due to the small number of pulses measured. Thus, the proposed system aims to be stable and to provide an accurate estimate of the dose rather than to provide a second-by-second dose fluctuation. Figure 4 shows a flowchart of the program's steps in the ESP32 microcontroller unit.

Our conversion factor assumes calibration against a Cs-137 gamma source in standard geometry, as published by the manufacturer in their datasheet [34] and confirmed by formal calibration at our National Authority for Nuclear, Radiological, Chemical and Biological Control (Baghdad, Iraq) according to ANSI N323-1996 standard (see Appendix A). This factor includes the tube sensitivity in CPS/(mR/h), conversion from roentgen soft tissue exposure to Sieverts (1 mR ≈ 8.77 μSv) and normalization from per-second to per-minute counting. The calibration certificate estimates uncertainty of this conversion factor at ±6%, which includes tube-to-tube production variation and dependence on scatter conditions due to geometry.

Besides the calibration uncertainty (±6%), the counting uncertainty of the Geiger-Müller detector has the characteristics of Poisson statistics, and may be estimated as:

$$\text{Relative Statistical Uncertainty} = \frac{1}{\sqrt{N}} \times 100\% \qquad (1)$$

where, N is the number of all the pulses measured within the measurement interval. During the 60 s integration time used in this study, the typical background radiation measured is (~22 CPM), which corresponds to a relative statistical uncertainty of (~21.3%). This uncertainty decreases as the count rate increases.

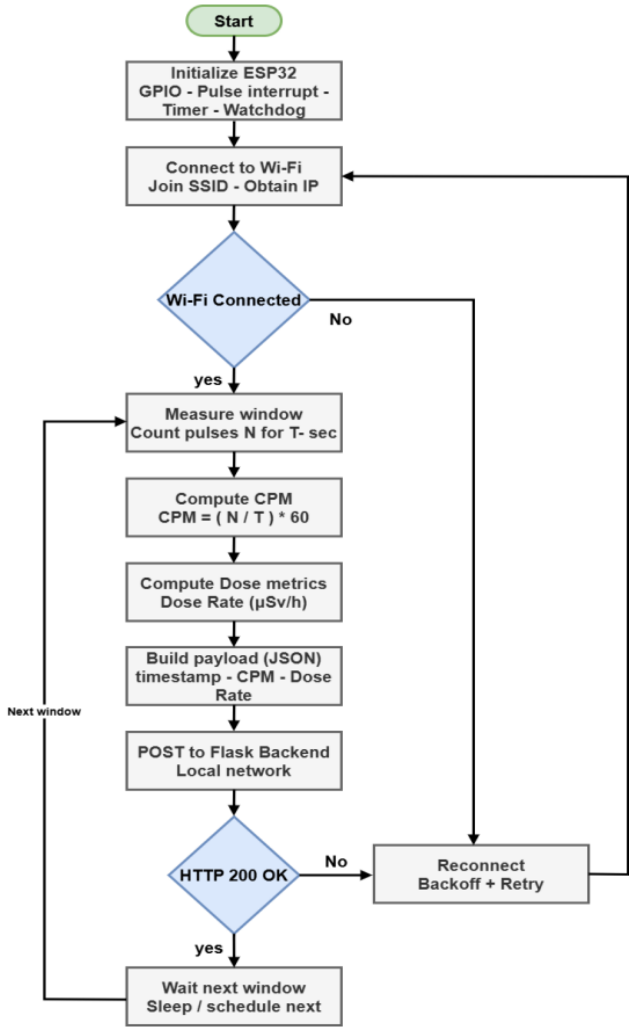


Figure 4. Flowchart of program steps in the ESP32 microcontroller unit

An additional validation experiment was performed using a commercial electronic personal dosimeter (Polimaster PM1703MO-1BT) to further confirm the performance of the proposed radiation monitoring system. Both devices were placed side by side in the same background radiation environment and measurements were taken simultaneously for several successive sampling periods. The comparison was carried out to test the consistency of the proposed system before the system is used in the clinical environment under a low dose of radiation.

The experimental validation of the proposed dosimeter with the reference electronic dosimeter Polimaster PM1703MO-1BT under the same background radiation conditions is presented in Figure 5.

As illustrated in the comparison, the reference dosimeter (Polimaster PM1703MO-1BT) and the proposed system are in good agreement within the range of background radiation levels tested. The observed deviations were kept within 5%, which falls within the range of the statistical variation of Geiger-Müller counters working at low-count rates. The outcomes outlined here offer further confidence in the accuracy of the proposed system for real-time monitoring of radiation in the occupation.

It is important to note that the comparison made in Table 1 is subjected to low-count background radiation and low-count ($K = 0.00332$) setting of the software. The setting was chosen to provide background-level verification with the reference dosimeter, with the count rate close to the natural background range. The final calibration-based conversion factor ($K = 0.0081$) was adopted for measurements in the cardiac catheterization environment for scattered radiation exposures during work activities, while the clinical measurements in this study were processed with the same conversion factor. Therefore, the values in Table 1 correspond to the background-validation mode and should not be interpreted using the clinical conversion factor given in Eq. (4).

Figure 5. Validations of the proposed dosimeter with the reference electronic dosimeter Polimaster

Table 1. Comparison between the proposed system and the Polimaster PM1703MO-1BT

Counts per Minute (CPM)	Estimated Dose Rate, μSv/h	Polimaster Meter, μSv/h	Difference, %
18	0.05976	0.06	0.4
21	0.06972	0.07	0.4
22	0.07304	0.07	4.3
24	0.07968	0.08	0.4
28	0.09296	0.09	3.3

3.4 Dose rate and cumulative dose computation

The conversion of pulse value CPM to dose rate and cumulative dose is based on the following mathematical relationships:

$$\text{CPM} = \frac{N}{T} \times 60 \tag{2}$$

where,
CPM: count per minute;
N: number of pulses;
T: time taken to measure pulses.

To convert these pulse counts in CPM into an equivalent dose rate in μSv/h, we rely on the physical characteristics of the SBM-20 tube as specified in the manufacturer's datasheet. The calibration dose rate, referenced to cesium-137 (Cs-137), is 4 μR/s, corresponding to a pulse count in the range of 240–280 CPS. The average value is then calculated as follows [34]:

$$\text{Average CPS} = \frac{240+280}{2} = 260 \text{ CPS} \tag{3}$$

This means that 260 CPS corresponds to 4 μR/s, which is equivalent to 65 CPS per μR/s, 18 CPS per mR/h, and 1080 CPM per mR/h. For the conversion from roentgen to sievert, 1 mR equals 8.77 μSv. To calculate the conversion factor K used for the SBM-20 tube, its value is determined by the following relationship:

$$\text{K} = \frac{8.77}{1080} = 0.0081 \tag{4}$$

The derived value of $K = 0.0081$ was consistent with the formal Cs-137 calibration of the complete dosimeter, which showed deviations of only 0–6% over the tested range of 8–80 μSv/h (Appendix A), indicating no significant discrepancy.
It is used to calculate the dose rate and cumulative dose:

$$\text{Dose Rate } (\mu\text{Sv/h}) = \text{K} \times \text{CPM} \tag{5}$$

$$Dose_{cum} = \sum_{i=0}^{M} (Dose\ Rate \times \Delta t) \tag{6}$$

where,
K: conversion factor;
CPS: count per second;
$Dose_{cum}$: cumulative dose.

3.5 Communication protocol used

The system sends data from the microcontroller (ESP32) through a Wi-Fi network using the HTTP protocol and JSON format to a backend server, achieving high response speed and facilitating data storage, analysis, and display. No retransmission mechanism in the application layer is implemented in the current implementation. The data are sent once a minute via HTTP over TCP/IP, which is a reliable transport-layer protocol that provide relieb transport. In case of a temporary Wi-Fi connection drop, the measurement is not performed and the next measurement is taken automatically when Wi-Fi is back up. During the four-week field deployment, no communication failures causing interruption of the monitoring process were observed.

3.6 Flask backend and data processing

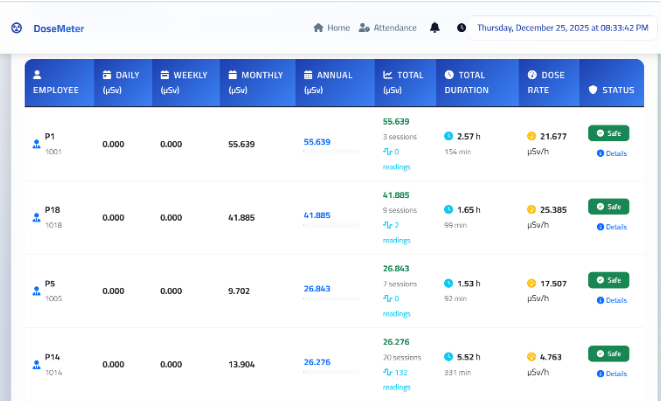
The system relies on a backend server built on the Flask environment, which receives data sent from the microcontroller (ESP32), analyzes it, stores it in a database (SQLite), and determines the total time of the received data, which leads to analyzing the data and performing long-term storage operations for cumulative doses. The SQLite database was used because of its high compatibility with Flask and reliability for editing data.

3.7 Web dashboard and user interface

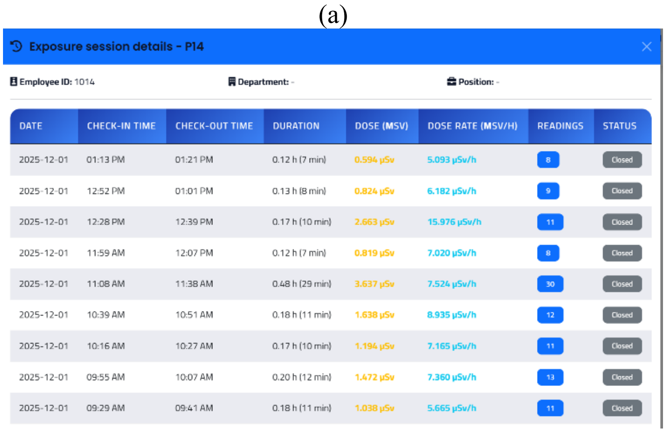
The web interface provides data display for users within the hospital environment, showing real-time radiation readings instantly. The system records all readings (daily, weekly, monthly, and annually) and displays the cumulative radiation total over a specific period. It sends alerts to the user interface, which has three levels (safe, warning-danger), with each level designated by a specific color for easy monitoring. In addition, it is possible to query, sort, and arrange according to exposure level and trigger alerts based on the value specified by the ICRP. Figure 6(a) and (b) show part of the system interface, as well as additional details for each person.

The dashboard's role is not limited to displaying readings; It is designed to support real-time preventive decisions during the procedure by displaying the dose rate in real time, tracking the cumulative dose for each individual, activating immediate alerts when thresholds are approached or exceeded, and displaying a historical record that helps the occupational safety officer analyze exposure patterns and identify procedures/conditions associated with high doses.

The web dashboard updates every minute because the CPM and dose rate shown are based on the previous 60-second time. The consequence is that the system offers current occupational dose data every minute, and a steady statistical dose rate for radiation protection monitoring.



(a)



(b)

Figure 6. Web dashboard of proposed radiation monitoring system: (a) main dashboard to monitor staff radiation readings and (b) individual staff exposure details for a selected staff member

4. IMPLEMENTATION AND TESTING

To test the system's suitability in a real-world environment, it was operated in the catheterization room at the Mosul Center for Cardiology and Cardiac Surgery (Iraq), where the device was carried by medical staff into the operating room and placed behind the lead apron worn by staff before entering the operating room. This dosimeter was worn below the lead apron and thus reflected the occupational dose behind the lead apron, not the unshielded scattered radiation field within the catheterization laboratory. The proposed system is supposed to be used as a post-protection occupational dose monitoring system for radiation safety management and is not considered a scattered radiation field detector. The natural background radiation within the hospital environment was measured, and the change in the reading was observed when approaching the radiation source. A clear variation was observed in the cumulative radiation value read according to the type of surgical procedure adopted by the attending physician, in addition to a variation in exposure levels according to the function assigned to each person inside the room. The system proved to be highly efficient for long periods of operation. The readings were monitored and recorded by one of the center's doctors, who performed nine operations on the same day, each with its own characteristics. All operations were recorded and the cumulative dose for the operations was calculated. The system was tested for a period of four weeks in the cardiac catheterization operating room, and the device was worn by all professionals involved in the operating room, where readings were recorded for doctors, physician assistants, radiographers, and physicists, who move around the room and do not have a fixed location like the rest of the staff. A clear difference was observed in the amount of exposure for each person depending on their location within the room and their distance from the radiation source.

The device was calibrated in the laboratories of the National Authority for Nuclear, Radiological, Chemical, and Biological Control (Baghdad, Iraq). Calibration was performed using a cesium source in accordance with ANSI N323-1996 standards, as shown in the document in Figure A1. An error rate ranging from 0% to 6% in radiation levels ranging from 8-80 μSv/h, which increases the reliability of the device for use in measurements in the catheterization room. The calibration certificate is provided in Appendix A.

5. RESULTS AND DISCUSSION

This section discusses the results of the system in the cardiac catheterization laboratory in terms of measurement accuracy, response time, transmission stability within the local network, and display of the indicated values for the dose rate and cumulative dose received in real time for the purpose of supporting occupational safety. Tests showed that the system can receive, store, and display readings instantly on the web interface. Since the cumulative count rate CPM is derived from a 60-second counting window, the system automatically updates once per minute.

One-minute integration time is chosen as a compromise between temporal resolution and counting accuracy, as a practical engineering solution. Shorter windows would result in noisier estimates in the low background and occupational dose rates common in cardiac catheterization laboratories due to limited counting statistics. Future versions of the system can optionally support 10-second or 30-second averaging modes for applications where detail in visualising trends is required, with 60-second mode as default for quantitative dose assessment.

It is worth mentioning that results described below are based on one operator, nine procedures conducted by a physician, and the busiest day in terms of procedures. This was done to demonstrate the ability of the system to track per-procedure exposures. The system was used consistently by all staff members (physicians, physician assistants, radiographers, and physicists) for four weeks. Data indicated stable system operation. We will apply the larger, multi-day and multi-operator dataset in future work to allow for increased statistical generalizability of exposure results. This design prioritizes stable counting statistics and eliminates second-by-second fluctuations, while still enabling professional monitoring in a real-time manner, where the average measured radiation background was approximately 22 CPM, equivalent to 0.17 μSv/h within the hospital environment. The system has demonstrated the ability to record cumulative doses (daily, weekly, monthly, annually) and trigger alerts when specified thresholds are exceeded. The system recorded numerous measurements for interventional catheterization procedures of varying purpose and complexity performed by a few physicians. We will discuss nine interventional catheterization procedures performed by one physician in a single day and show the dose rate and cumulative dose for each procedure and the time required. The average dose per procedure was 1.54 ± 1.00 μSv (Mean ± standard deviation (SD)) and the average dose rate ranged from a minimum of 5.09 μSv/h to a maximum of 15.98 μSv/h, with an overall average of 7.88 μSv/h and a total daily cumulative dose of 13.879 μSv. Table 2 shows the detailed dose recorded for each of the nine interventional procedures, including the time taken for each procedure, the cumulative dose, and the dose rate.

Table 2. Detailed parameters of interventional procedures

Procedure No.	Duration, min	Cumulative Dose, μSv	Dose Rate, μSv/h
1	11	1.038	5.665
2	12	1.472	7.36
3	10	1.194	7.165
4	11	1.638	8.935
5	29	3.637	7.524
6	7	0.819	7.02
7	10	2.663	15.976
8	8	0.824	6.182
9	7	0.594	5.093

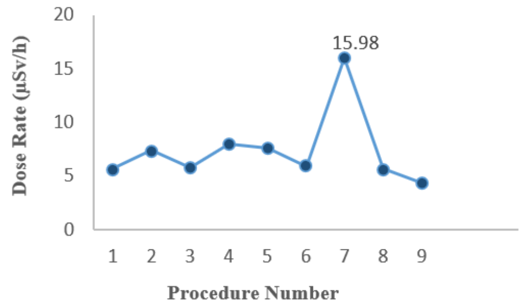
Figure 7 also illustrates the variation in radiation exposure levels. Figure 7(a) shows the variation in cumulative dose rates, with a clear peak observed in case No. (7), reaching 15.976 μSv/h, and Figure 7(b) shows the variation in cumulative dose between a minimum of 0.594 μSv in case No. (9) and a maximum of 3.637 μSv in case No. (5).

The standard deviation of cumulative dose (SD = ±1.00 μSv/procedure) among procedures can be attributed to variations in technical difficulty, intensity of fluoroscopy use, and distance maintained from the source by the physician. Although case No. 7 had a relatively short procedure time (10 minutes), it registered the highest dose rate of 15.98 μSv/h, indicating a procedure of increased technical difficulty requiring prolonged periods of fluoroscopy use. Results are like findings by Madder et al. [31], which revealed high outlier cases to contribute significantly more dose than the average occupational dose.

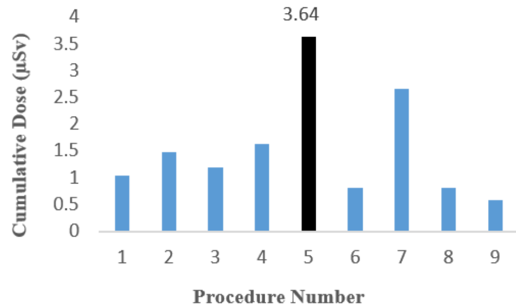
$$D_{eq} = \frac{20000\ \mu Sv}{365} = 54.8\ \mu\text{Sv/day} \tag{7}$$

where, D_{eq} represents the calendar day equivalent of the annual occupational dose limit.

The annual occupational dose limit recommended by the ICRP is 20,000 μSv/year, which was converted into an equivalent dose per calendar day (54.8 μSv/day). The total dose during the shift analysed (13.88 μSv) is around 25.3% of this calculated daily equivalent. This comparison is made only to give a practical guide to the dose measured and is not an official daily dose limit. These doses fall within the range of reported occupational doses by Murat et al. [25] and Ageel [30], who studied occupational doses received by interventional cardiology personnel.



(a)



(b)

Figure 7. Variation in radiation exposure across the nine procedures: (a) dose rate and (b) cumulative dose per procedure

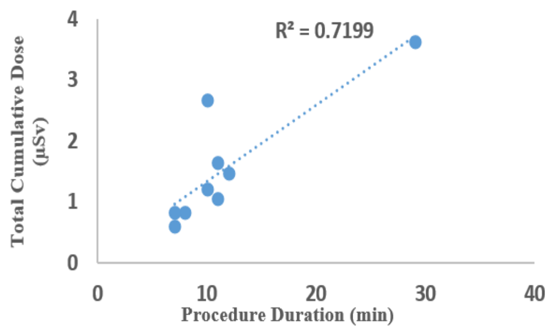


Figure 8. Correlation between procedure duration and cumulative dose

To understand the reason for this variation, a relationship was established between the time required for each invasive procedure and the cumulative dose recorded during this period, as shown in Figure 8. Data analysis revealed a coefficient of determination $R^2 = 0.7199$, showing a relationship between procedure time and cumulative dose, with two different patterns emerging. The first is related to the duration of the interventional procedure, with case No. (5) being the highest due to the length of time, which was 29 minutes. The second pattern depends on the increase in radiation intensity and the level of protection used, as observed in case No. (7), where the time period for the interventional procedure was 10 minutes, while the cumulative dose was 2.663 μSv, which is considered high for the time period required, and is attributed to the cumulative dose rate, which reached 15.976 μSv/h. This indicates that high-intensity radiation can cause significant exposure even during short periods of time.

The detailed case study above is complemented with a summary of measurements taken during one representative week in Table 3 and Figure 9. The table displays the number of procedures as well as the maximum and average dose per day over the specified period. The radiation exposure depended on clinical workload and the nature of the procedure; however, the proposed monitoring system worked around the clock and was uniform during the period of observation. The observed trend shows the ability of the system to pick up the day-to-day changes in occupational radiation exposure without any significant upset to the system.

Table 3. Weekly trend of mean cumulative occupational radiation dose

Date	Procedures	Mean Dose, μSv	Max Dose, μSv	Total Daily Dose, μSv
Nov. 17	4	2.281	3.90	9.12
Nov. 18	4	2.153	3.65	8.61
Nov. 19	4	2.430	3.46	9.72
Nov. 20	4	3.035	6.66	12.14

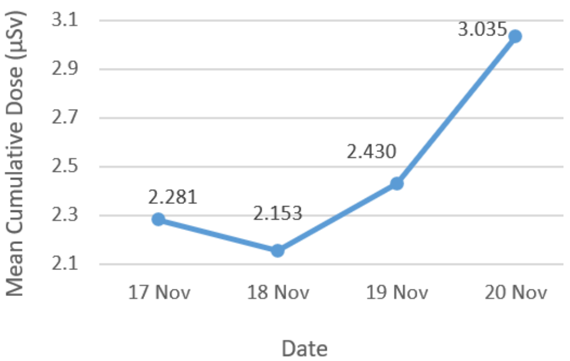


Figure 9. Weekly variation in the average cumulative radiation dose

6. CONCLUSIONS

This paper developed an IoT system for real-time monitoring of radiation levels and providing real-time feedback in the cardiac catheterization laboratory, relying on a wireless microcontroller (ESP32), a local server, and an interactive web interface. The system was practical and low-cost. The results, based on data stored in the SQLite database, showed that the system can record the dose rate in real time and display it immediately, in addition to calculating the cumulative dose over time to support occupational exposure assessment. An increase in the cumulative dose level was observed for one of the procedures due to the length of time the procedure takes, while an increase in the radiation dose rate was observed in another procedure despite the short time the surgical procedure takes. This was due to the need to use high radiation levels, which caused an increase in the dose rate. Future work might involve expanding the system to include a machine learning algorithm fed with past exposure session data that could potentially forecast high-risk procedures prior to their taking place. Characteristics such as type of procedure, estimated time, role of operator, etc. could all be factored into such a model to trigger alerts and automatically control exposure in real time.

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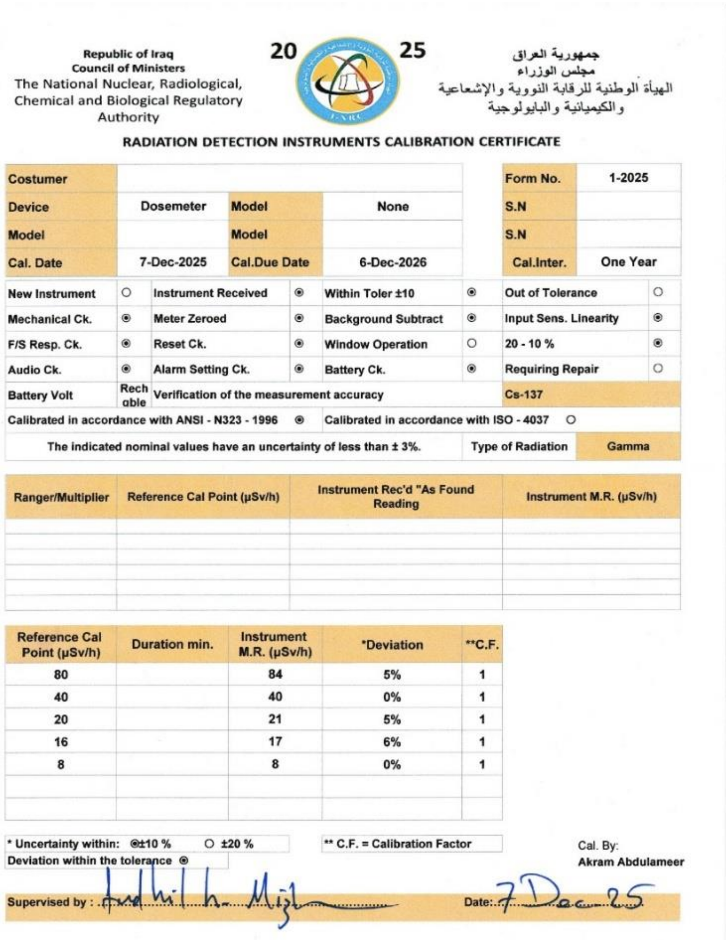
APPENDIX



Republic of Iraq
Council of Ministers
The National Nuclear, Radiological, Chemical and Biological Regulatory Authority

20 25

جمهورية العراق
مجلس الوزراء
الهيأة الوطنية للرقابة النووية والإشعاعية والكيميائية والبايولوجية

RADIATION DETECTION INSTRUMENTS CALIBRATION CERTIFICATE

Costumer					Form No.	1-2025
Device	Dosemeter	Model	None		S.N	
Model		Model			S.N	
Cal. Date	7-Dec-2025	Cal.Due Date	6-Dec-2026		Cal.Inter.	One Year

New Instrument	○	Instrument Received	◉	Within Toler ±10	◉	Out of Tolerance	○
Mechanical Ck.	◉	Meter Zeroed	◉	Background Subtract	◉	Input Sens. Linearity	◉
F/S Resp. Ck.	◉	Reset Ck.	◉	Window Operation	○	20 - 10 %	◉
Audio Ck.	◉	Alarm Setting Ck.	◉	Battery Ck.	◉	Requiring Repair	○
Battery Volt	Rechable	Verification of the measurement accuracy				Cs-137	

Calibrated in accordance with ANSI - N323 - 1996 ◉ Calibrated in accordance with ISO - 4037 ○

The indicated nominal values have an uncertainty of less than ± 3%. Type of Radiation: Gamma

Ranger/Multiplier	Reference Cal Point (μSv/h)	Instrument Rec'd "As Found Reading	Instrument M.R. (μSv/h)

Reference Cal Point (μSv/h)	Duration min.	Instrument M.R. (μSv/h)	*Deviation	**C.F.
80		84	5%	1
40		40	0%	1
20		21	5%	1
16		17	6%	1
8		8	0%	1

* Uncertainty within: ◉±10 % ○ ±20 %
** C.F. = Calibration Factor
Deviation within the tolerance ◉

Cal. By:
Akram Abdulameer

Supervised by : .... Date: 7 Dec 25

Figure A1. Calibration certificate