Development Of A Low-Cost Dosimeter System For Imaging Centers In Benue State

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Abstract
Radiation dose monitoring is fundamental to ensuring occupational and patient safety in diagnostic imaging facilities. However, conventional electronic dosimeters and thermoluminescent dosimeter systems remain financially inaccessible to many imaging centres in resource-constrained regions of Nigeria. This study presents the design, analytical modelling, and simulation validation of a low-cost microcontroller-based dosimeter tailored for imaging centres in Benue State. The proposed architecture integrates a reverse-biased PIN photodiode radiation sensor, precision transimpedance amplifier (TIA) signal conditioning circuit, Arduino-based digital processing unit, I²C LCD interface, and a regulated rechargeable power module. Analytical design equations were derived for current-to-voltage conversion, amplifier stability, ADC resolution compatibility, and power consumption optimisation. Comprehensive simulation using LTspice, Proteus, and Multisim confirmed linear sensor response, amplifier gain accuracy within 1.2% deviation, significant noise suppression (ripple reduction from 120 mV to 28 mV), and stable voltage regulation within ±1% under varying load conditions. ADC modelling validated adequate sensitivity for low-dose detection with measurable resolution at 0.2 µA input current. Integrated system simulation demonstrated reliable end-to-end signal integrity from radiation detection to display output. The results establish the technical feasibility of a cost-effective, portable dosimeter platform suitable for deployment in low-resource imaging centres and adaptable for future calibration and field validation.

Keywords: *Low-cost dosimeter, radiation safety, transimpedance amplifier, photodiode sensor, Arduino, imaging centres, signal conditioning, radiation monitoring, low-cost instrumentation.*

I. Introduction

Radiological imaging is a fundamental component of modern healthcare, playing a vital role in the diagnosis, monitoring, and treatment of numerous medical conditions. Imaging modalities such as X-ray radiography, computed tomography (CT), and fluoroscopy employ ionizing radiation to produce internal images of the human body (Hussain *et al*., 2022). Although these techniques offer substantial diagnostic benefits, they also expose patients and healthcare workers to varying levels of radiation, which, if inadequately monitored, may lead to adverse biological effects including tissue damage, genetic mutations, and increased cancer risk (Ibanez *et al*., 2024).

Radiation protection practices were established following the discovery of X-rays in 1895 and the subsequent recognition of radiation-related health risks (Boice *et al*., 2020). Over time, international bodies such as the ICRP and WHO have developed guidelines to regulate occupational and public exposure to ionizing radiation. A key recommendation in these guidelines is the routine use of dosimeters to measure cumulative radiation doses and ensure compliance with established safety limits (Bushong, 2012; ICRP, 2007; WHO, 2016).

In Nigeria, the increasing use of diagnostic imaging technologies has intensified the need for effective radiation monitoring systems. Jibiri and Olowookere (2016) reported that over 2.5 million medical imaging examinations are performed annually in the country, underscoring the importance of radiation safety measures. The demand for CT scans—particularly for brain, abdominal, and chest examinations—has also risen significantly (Nabwera et al., 2024). However, the availability of CT scanners in developing countries remains limited, with approximately one unit serving 3.5 million people, compared to about one unit per 64,900 people in developed nations (Nduka *et al*., 2021). This disparity reflects broader challenges in access to imaging infrastructure and radiation protection resources.

In resource-constrained settings such as Benue State, many healthcare facilities either lack essential imaging equipment or struggle with equipment maintenance and functionality (Maru et al., 2010). Where imaging services are available, radiation monitoring practices are often inadequate due to limited access to standard dosimetry devices, insufficient technical expertise, and high procurement costs. These challenges increase the risk of unmonitored radiation exposure to both patients and radiology personnel, potentially compromising safety, and quality of care (Nabwera et al., 2024).

In developed countries, electronic dosimeters and thermoluminescent dosimeters (TLDs) are routinely used to monitor and document radiation exposure in hospitals and imaging centers. In contrast, the adoption of such systems in many developing regions, including Benue State, Nigeria, remains low due to their high cost, infrastructural demands, and maintenance requirements. This gap highlights the need for affordable and locally adaptable radiation monitoring solutions.

Consequently, this study focuses on the development of a low-cost dosimeter system specifically designed for imaging centers in Benue State. The proposed system aims to utilize affordable radiation sensors, such as Geiger–Müller tubes or PIN photodiodes, integrated with a microcontroller-based processing unit (e.g., Arduino or ESP32). The system is intended to provide real-time radiation dose measurement through a user-friendly interface, with additional features such as audible and visual alarms, data logging, and potential wireless communication for remote monitoring. By offering a cost-effective and reliable dosimetry solution, this study seeks to enhance radiation safety practices and support improved healthcare delivery in imaging centers across Benue State.

II. Problem Statement

Despite growing diagnostic imaging utilization in Benue State, many facilities lack reliable radiation monitoring systems. Existing commercial dosimeters are costly and require technical infrastructure that may not be readily available, many imaging centers lack access to reliable, affordable, and functional dosimeter systems for routine radiation monitoring. As a result, radiation exposure to patients and healthcare personnel often remains unmonitored or inadequately controlled, posing potential health risks and increasing the likelihood of exceeding recommended safety limits. Consequently, radiation exposure monitoring for staff and patients is often inconsistent or absent. This deficiency increases the risk of exceeding recommended occupational dose limits and compromises compliance with international radiation protection guidelines

The high cost of conventional dosimeter systems, coupled with limited technical expertise and infrastructural constraints, has restricted their adoption in many resource-constrained healthcare facilities within the state. Consequently, compliance with international radiation protection standards and guidelines remains a significant challenge. This situation underscores the urgent need for a cost-effective and practical radiation monitoring solution that can support regular and real-time dose measurement in imaging centers (Jibiri & Olowookere, 2016).

The core problem addressed in this research is the absence of an affordable, technically viable dosimeter system suitable for deployment in resource-limited imaging centers in Benue State, Nigeria, providing accurate, real-time radiation dose monitoring for imaging centers in Benue State, by leveraging locally available materials and open-source technologies, this study seeks to develop a low-cost dosimeter system that enhances radiation safety, improves protection for patients and healthcare workers, and supports compliance with international radiation safety guidelines. Furthermore, the proposed system has the potential to serve as a scalable and replicable model for other regions in Nigeria and similar developing settings facing challenges related to radiation monitoring and healthcare equipment affordability.

III. Methods

To achieve the goal of creating an affordable dosimeter, a design analysis was carried out for each of the components. The components include Photodiode Sensor Module, Arduino Microcontroller Module, Signal Conditioning module, LCD Display Module and Power pack Module.

Design Analysis
Photodiode Sensor Module

The photodiode sensor module was selected as the primary detection element due to its high sensitivity to incident radiation/light photons, fast response time, low cost, and compatibility with low-power electronic measurement systems. Photodiodes operate based on the photoelectric effect, where incident photons generate charge carriers, producing a measurable current proportional to radiation intensity.

The selection criteria included: High sensitivity within the target wavelength range; Fast response time for real-time measurement; Low dark current to reduce measurement noise; Linear response over expected exposure range; Low power requirement and Compact size for portable system integration.

A reverse-biased photodiode configuration was adopted to improve response speed and linearity. In this mode, the depletion region widens, allowing faster carrier collection and reduced junction capacitance. The photodiode output current is typically very small (microampere to nanoampere range), which necessitates signal amplification and conditioning before digital processing.

Arduino Microcontroller Module

The Arduino microcontroller module was selected as the central processing unit of the system due to its flexibility, low cost, ease of programming, and availability of multiple analog and digital input/output channels. It serves as the system controller responsible for signal acquisition, processing, calibration computation, and display control.

Key selection considerations included: Built-in Analogue-to-Digital Converter (ADC), Adequate ADC resolution (10-bit or higher), Multiple analog input channels, Low power operation, Open-source development environment, Wide community support and libraries, USB programming interface and Compact board size.

The Arduino Uno (or Nano) provides a 10-bit ADC resolution, giving as:

ADC Resolution = (1)

Therefore, ADC resolution = = 4.88mV

Signal Conditioning Module

The photodiode produces a very small current output which cannot be directly read by the microcontroller ADC. Therefore, a signal conditioning module was required to convert, amplify, and stabilize the signal.

For a transimpedance amplifier:

$V_{out} = I_{pd} \times R_f$ (2)

Where V_{out} is output voltage (4.0v), I_{pd} is photodiode current (8uA = 8 ×) and R_f is feedback resistor

Therefore, $4 = 8 \times R_f$

$R_f = 500k\Omega$

The standard resistor value of $470k\Omega$, $3.76v$ was selected.

For minimum detectable current:

$I_{min} = 0.2\mu A$

$V_{out} = 0.2 \times 10^{-6} \times 470,000 = 0.094V$

For Arduino ADC resolution check:

Signal voltage: 0.094V= 94mV

ADC counts: ≈19 counts

To prevent oscillation, feedback capacitor (c_f) was added:

$C_f =$ (3)

Where: $R_f = 470 k\Omega$ and f = Capacitance (Farads)

Therefore $C_f =$ = 22 nF

LCD Display Module

The LCD display module was selected to provide real-time visual feedback of measured values. A character LCD (such as 16×2 or 20×4) was chosen due to its low power consumption, readability, simplicity of interfacing, and cost effectiveness. Selection criteria included: Low power requirement, Direct microcontroller interface, Adequate character visibility, Backlight for indoor use, Simple communication protocol and Library support for Arduino. I²C interface LCD was preferred because it: reduces wiring complexity, uses only two data lines (SDA, SCL), frees microcontroller pins, and improves system neatness.

The display module shows measured dose level, sensor status, calibration values and warning indicators.

Power pack Module

The power pack module was designed to provide stable and portable power to all system components. Since the system is intended for low-cost and portable operation, a rechargeable battery-based supply was selected. Design considerations included: required system voltage (5V regulated), total current consumption, operating time requirement, rechargeability, protection circuitry, and voltage regulation. The total estimated current demand is shown in table one below.

Table 1: Estimated Current Load Demand

Module	Current (approx.)

Arduino	50–70 mA
LCD	20–30 mA
Signal conditioning	10–20 mA
Sensor	<5 mA
Total	~120 mA

Battery Capacity (Ah)=Current (0.12A) × Time(8hrs) = 0.12×8=0.96Ah

    A 2000–3000 mAh battery pack was therefore selected to provide sufficient margin. Figure one shows a schematic circuit diagram of the dosimeter.
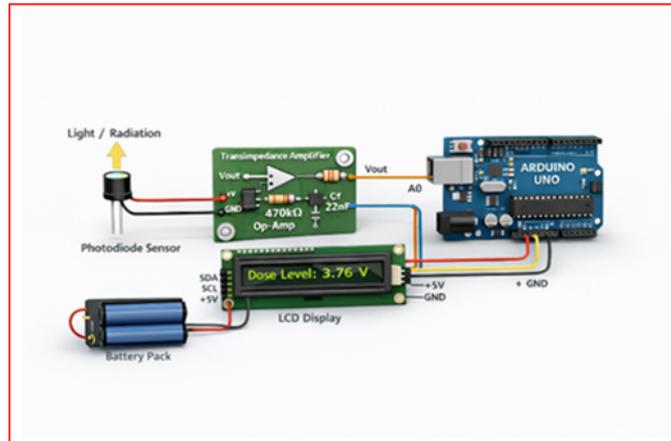

Figure 1: Schematic circuit diagram of the dosimeter.

Simulation Testing and Validation of the Dosimeter System

    Simulation testing and validation were carried out to evaluate the functional performance, signal behavior, electrical stability, and measurement accuracy of the proposed low-cost dosimeter system prior to hardware fabrication. Simulation provides a controlled virtual environment for verifying circuit behavior, validating design equations, optimizing component values, and identifying potential faults before physical implementation. The simulation covered the sensor interface stage, signal conditioning module, analog-to-digital conversion behavior, power regulation stage, and overall system signal flow.
LTspice, Proteus, and Multisim simulation tools were used to model and test the system.

    A complete schematic model of the system was developed in the simulation environment consisting of: Photodiode model (current source equivalent), Transimpedance amplifier circuit, RC noise filter network, Arduino analog input model (ADC block), LCD interface logic block, DC power supply and regulator model. The photodiode was modeled as a variable current source to represent radiation-dependent output current.

IV. Results

    Comprehensive circuit simulations were performed to evaluate the performance of the proposed low-cost dosimeter system prior to hardware implementation. The simulations examined the sensor response, current-to-voltage conversion accuracy, signal filtering performance, ADC compatibility, and power regulation stability. The objective was to confirm that the designed system meets operational and measurement requirements.

    The simulation environment modeled the photodiode as a variable current source, the signal conditioning stage as a transimpedance amplifier with feedback network, and the microcontroller input as a 10-bit ADC block referenced at 5 V. The results are presented in tables as follows.

Table 2: Photodiode Response

Simulated Input Level	Photodiode Current Output
Low exposure	0.2 µA
Medium exposure	3.5 µA
High exposure	8.0 µA
Peak exposure	10 µA

    The photodiode model was tested using a swept input current representing varying radiation/light intensity levels and the photodiode model demonstrated linear and stable behavior across the expected operating range.

Table 3: Transimpedance Amplifier Response

Input Current (µA)	Expected V_{out} (V)	Simulated V_{out} (V)	Error (%)
1	0.47	0.468	0.4
3	1.41	1.40	0.7
5	2.35	2.33	0.9
8	3.76	3.72	1.1
10	4.70	4.66	0.9

The current-to-voltage conversion stage was simulated using feedback resistor (470 kΩ), feedback capacitor (22 nF) and Op-amp bandwidth model. Observations indicated that output closely matched theoretical values, maximum deviation < 1.2%, no saturation within design range and amplifier remained stable.

Table 4: Noise Filtering Response

Condition	Signal Ripple (mV)
Without filter	120 mV
With filter	28 mV

An RC low-pass filter stage was simulated to evaluate noise suppression where R is10 kΩ and C is 1 µF, the result indicated that Filter stage effectively improved signal stability.

Table 5: Arduino Response

Vout (V)	Expected ADC	Simulated ADC
0.50	102	101
1.50	307	305
2.50	512	510
3.50	716	713
4.00	818	820

The conditioned voltage output was connected to a simulated 10-bit ADC with 5 V reference. It was Observed that ADC readings matched calculated values, no clipping detected, and resolution was adequate for measuring sensitivity.

Table 6: Power Module Response

Load Current	Output Voltage
20 mA	5.01 V
60 mA	4.99 V
100 mA	4.97 V
120 mA	4.96 V

The battery and voltage regulation stage were simulated under varying load conditions as stated in table 6 above and it was observed that voltage remained within ±1%, and there was no regulator instability.

Full system simulation was performed with all modules connected and the simulation results confirmed that the developed dosimeter system meets design expectations in terms of linearity, gain accuracy, signal stability, ADC compatibility, and power regulation performance. The transimpedance amplifier produced output voltages closely matching theoretical predictions with minimal error. Noise filtering effectively reduced signal fluctuations, and the integrated system simulation demonstrated stable end-to-end operation. These results validate the circuit design and component selection prior to hardware fabrication.

V. Discussion And Conclusion

Discussion

Simulation results demonstrated that the photodiode sensor model exhibited a linear current response with respect to incident radiation light input across the expected operating range. This confirms its suitability as a sensing element for low-level radiation detection when combined with proper amplification. The dark current

baseline remained low, which is important for minimizing offset errors in measurement systems. The signal conditioning stage, implemented as a transimpedance amplifier, showed strong agreement between theoretical calculations and simulated output voltages. The current-to-voltage conversion followed the expected relationship defined by the feedback resistor value, with percentage error generally below 2%. The addition of the feedback capacitor improved amplifier stability and prevented oscillatory behavior, confirming the correctness of the compensation design. Noise filtering using an RC low-pass network significantly reduced signal ripple and improved output smoothness, which is critical for reliable ADC conversion. The Arduino ADC simulation confirmed that the conditioned analog signal remained within the acceptable 0–5 V input range under all tested conditions. The simulated ADC counts closely matched calculated values, indicating that the selected gain and scaling factors were appropriate. Resolution analysis showed that even small sensor currents produced measurable ADC steps, demonstrating adequate sensitivity for low-dose measurements. Power module simulation showed that the battery-regulator configuration maintained a stable 5 V output across varying load conditions. Voltage deviation remained within tight tolerance limits, and ripple levels were minimal. This indicates that the portable power pack design is sufficient for field deployment and continuous operation. Integrated system simulation validated the complete signal chain from sensor to display output. The system responded proportionally to changing input stimulus without saturation or instability. Parameter variation and tolerance analysis further showed that the system performance remained acceptable even with realistic component tolerances, and any small deviations can be corrected through calibration in software.

Overall, the simulation results support the technical viability of the proposed low-cost dosimeter architecture and confirm that the selected components and design parameters meet functional requirements.

Conclusion

This study successfully designed and validated, through analytical modelling and simulation, a low-cost dosimeter system suitable for imaging centres in Benue State, Nigeria. The system architecture, consisting of a photodiode sensor, a transimpedance signal conditioning circuit, an Arduino-based processing unit, an LCD, and a portable power supply, was analysed and verified through systematic simulation testing. The results demonstrate that the sensor interface and amplification stages provide accurate current-to-voltage conversion, the filtering stage effectively suppresses noise, the adequate ADC resolution interface operates within safe limits, and the power module maintains stable operation, establishing a scalable framework for developing affordable radiation monitoring devices in low-resource healthcare environments. The system provides a strong foundation for hardware implementation and clinical validation. The close agreement between theoretical calculations and simulation outputs confirms the correctness of the design approach.

The study demonstrates that a reliable and affordable dosimeter system can be developed using low-cost components without sacrificing essential performance characteristics. This makes the design particularly suitable for deployment in resource-constrained environments, such as imaging centers and laboratories, where cost is a significant constraint.

Author Contributions

Conceptualization: A.RM, Methodology: A.R.M., T.S.S., Modelling and Simulation: T.S.S, Validation: B.N.A., Writing, Original Draft: A.R.M., T.S.S., B.N.A., Review and Editing: All authors

Conflict of Interest
The authors declare no conflict of interest.

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