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Design and Development of a Radiation Dose Measurement Tool Using The Geiger Muller Sensor With ESP-32 Based On The Internet of Things (IoT)

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Abstract

This study aims to develop a cost-effective and accurate prototype for monitoring X-ray radiation leakage using an Internet of Things (IoT)-based system. The primary goal is to design and test a radiation dose measurement tool equipped with a Geiger-Müller detector and an ESP-32 microprocessor, integrated with the cloud-based platform ThingSpeak for real-time data communication. The prototype was evaluated for its operational performance and ability to detect radiation leakage from Mobile X-ray and Fluoroscopy tubes. Experimental results show that the device achieved a measurement error of less than 5% when compared to the SE International Ranger survey meter. In Mobile X-ray testing, the highest error was recorded in Area 4 (left) at 4.00%, and the lowest in Area 3 (right) at 1.63%. In Fluoroscopy testing, the highest error occurred in Area 3 (right) at 4.80%, and the lowest in Area 4 (left) at 1.43%. Both the prototype and the standard survey meter confirmed that leakage levels from the tested equipment complied with Indonesia's Ministry of Health Regulation No. HK.02.02/V/5771/2018, maintaining radiation levels (L) below 1 mGy/h.

Keywords: *Surveymeter, X-ray tube, leak test.*

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1. INTRODUCTION

Nuclear science and technology have rapidly advanced in recent years. Various fields such as energy, medicine, environment, water, food, agriculture, astronomy, material industries, and structural component investigation have benefited from its applications (Ahmad et al., 2021). In the medical field, X-ray radiation has proven to be highly useful and beneficial (Shi, Sun & Ju, 2022; Luan et al., 2021). Although prolonged exposure to X-ray radiation at certain dose levels can pose serious risks to human living cells (Al-Qabandi & Alshammary, 2022), its advantages far outweigh the risks especially in therapeutic treatments and the diagnosis of specific organs.

The probability and magnitude of risks potentially caused by X-ray radiation can be minimized if X-rays are used appropriately, avoiding excessive and unnecessary exposure. The medical community must play a crucial role not only in restoring health but also in protecting and promoting it (Chowdhury S et al., 2017). The International Radiation Protection Association (IRPA) has developed several guidelines to limit radiation doses received by healthcare workers (Hesaraki M et al., 2021). Likewise, the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) have issued recommendations that are referenced by nuclear energy regulatory bodies in each country. In 1990, through Publication No. 96 on Radiation Protection (Sowby FD et al., 1981), the ICRP reaffirmed the standard system of radiological protection by recommending lower dose limits for radiation workers and the general public. The maximum allowable dose for radiation workers is 5 mSv per 3 months, 20 mSv per year, or no more than 100 mSv over 5 years.

Artificial ionizing radiation, such as X-rays, cannot be detected by human sensory organs, and can only be identified using dedicated X-ray monitoring equipment (Holovatyy A et al., 2020). In this context, the existence of an X-ray radiation monitoring system in X-ray facility workspaces becomes crucial especially one that can operate wirelessly and be integrated with various communication devices. Today, the Internet of Things (IoT) technology has advanced rapidly and is widely applied in various fields, including digital healthcare, smart buildings, smart cities, intelligent transportation systems, logistics, energy conservation, and more (Zhao H et al., 2022). Supported by the availability of various detector or sensor technologies, microprocessors, and software systems, there is great potential to develop a prototype design for an intelligent X-ray radiation monitoring system.

To date, one of the most essential components in instrumentation design is the microcontroller, such as the Arduino Uno. However, the Arduino Uno is not fully optimized for Internet of Things (IoT)-based systems, as it requires additional external modules for internet connectivity such as Wi-Fi or Bluetooth. In response to this limitation, Arduino, in collaboration with Espressif, released the ESP-32 microcontroller, which integrates both Wi-Fi and Bluetooth capabilities making it highly suitable for IoT-based prototype development (Widyatmika et al., 2021).

In 2019, Duwi Hariyanto and Sidik Permana conducted a study titled "Radiation Intensity Study Using a Survey Meter Based on Geiger M4011 Tube and Arduino Uno Microcontroller". The device used the M4011 Geiger tube as its detector and reported a measurement error of approximately ±5%. Similarly, in 2021, Muhammad Isa Dzulqarnain developed a digital pocket dosimeter using a Geiger Muller SI-29BG tube with web-based dose data storage, obtaining an error of 3.65% compared to a commercial survey meter.

Further research by Wahyu Pratama et al. (2022), titled "Analysis of the Geiger Muller Ability on the Effect of Collimation Area and Irradiation Distance on the Dose of X-Ray Machine Measurements", used a prototype device with a Geiger Muller counter and Arduino Nano, with results read via computer. The study found percentage errors of 4.05% (10×10 cm collimation), 2.13% (20×20 cm), and 0.36% (30×30 cm), when compared with standard dosimeters.

The development of this device represents an advancement in the prototype design of an X-ray radiation monitoring system, based on a Geiger-Müller detector and an ESP-32 microprocessor, integrated with a cloud-based communication platform, ThinkSpeak. This system offers improved accuracy and incorporates a modern Internet of Things (IoT) framework.

2. METHODS

Design and Development of a Radiation Dose Measurement Device Using a Geiger–Müller Sensor with ESP-32 Based on the Internet of Things (IoT). To design and develop a radiation dose measurement device featuring a Geiger–Müller sensor and ESP-32 for IoT, a detailed research and development approach is required. This study adopts the Research and Development (R&D) methodology a powerful strategy for improving practical implementations.

The Research and Development (R&D) method is highly suitable for this study, as it begins with field observations aimed at identifying potential risks and issues that may lead to future losses. A more in-depth assessment revealed the adverse effects of ionizing radiation on radiation workers, as well as the high cost of commercially available radiation measuring instruments. Following these observations, relevant information was gathered to support the development of the measurement device. This information includes identifying the necessary components for designing the instrument, such as the selection of an appropriate microcontroller, sensor, and Internet of Things (IoT) system.

The device is designed at the Physics Laboratory of Universitas Nasional, located at Jl. Bambu Kuning No. 8, RT 4/RW 1, Jati Padang, Ps. Minggu, South Jakarta, Special Capital Region of Jakarta.

Research Materials and Equipment

During the design phase, both hardware and software components needed for the IoT-based Geiger–Müller radiation dose measurement device were developed.

Hardware Design

The following tools and materials are required :

1. Geiger–Müller Counter Module (GM V1.1)

This module serves as the main component supporting the performance of the Geiger-Müller tube in carrying out its detection function. It is equipped with a speaker that provides an audible signal when radiation is detected, and an Organic Light Emitting Diode (OLED) display that indicates the module is in operation. The circuit diagram of the module is presented in Figure 1 below :

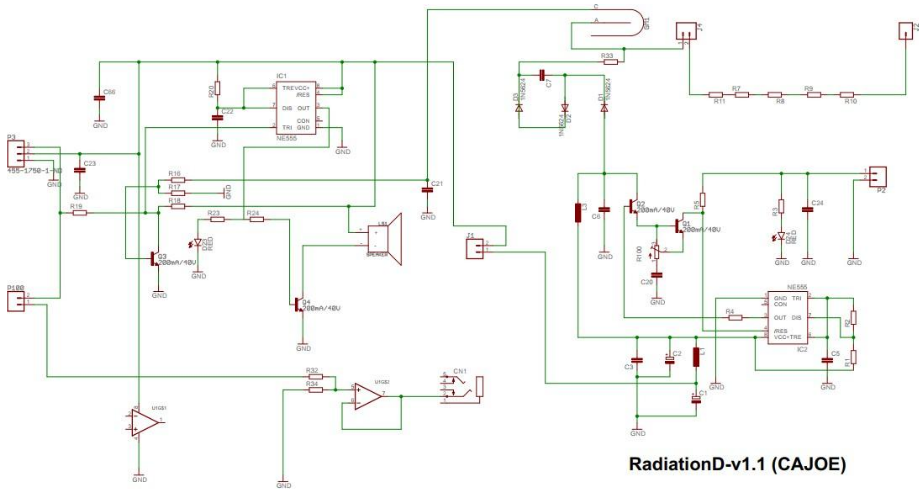

Figure 1. The module schematic

2. ESP-32 Module with OLED Display
   The ESP-32 module functions as the central processing unit that receives and processes electrical signals generated by the Geiger-Müller Counter module (GM V1.1) when ionizing radiation is detected. The processed data is then displayed in real-time on an integrated Organic Light Emitting Diode (OLED) screen for local monitoring. Additionally, the ESP-32 transmits the data via Wi-Fi to the cloud-based IoT platform ThingSpeak, enabling remote access and continuous data logging. The ESP-32 operates through a wireless connection, making it suitable for Internet of Things (IoT) applications in radiation monitoring systems.
3. Charging Module
   This module serves as a battery charger and features built-in battery protection to optimize charging and extend battery life. The module circuit can be seen in Figure 2.

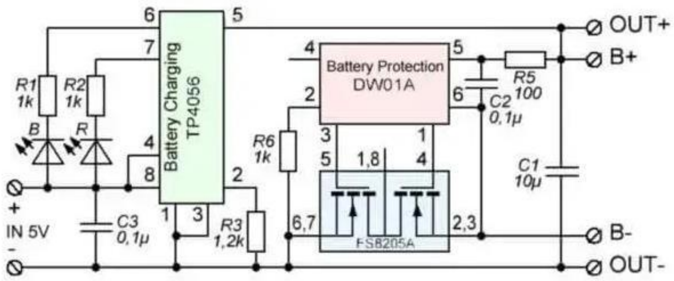

Figure 2. the schematic

4. Battery. A rechargeable Li-ion 18650 battery provides the main power supply for the entire system.
5. Jumper Wires. These cables connect the charger module to other circuit components.
6. USB Data Cable. A USB-B cable connects the ESP-32 to a laptop for programming via the Arduino IDE.
7. Acrylic Sheet. Used to make the device's cover. Acrylic is chosen for its low cost, ease of availability and shaping, and relative sturdiness.
8. Laptop. Used for programming in Arduino IDE. Specs: Intel Celeron, 2 GB RAM, Windows 7 32-bit.

9. Electric Drill. Employed to drill holes in the acrylic for module feet, switches, and charger connectors.
10. Soldering Iron and Solder. Used to connect the battery to the charging module.
11. Heat Gun. Used to shape the acrylic according to the design specification.

Data Collection and Analysis Technique

Hardware integration involves connecting all the components: the charger module provides approximately ±4 V DC to both the Geiger–Müller counter module and the ESP-32 microcontroller. Once powered, the Geiger–Müller module becomes active indicated by an LED and simultaneously the ESP-32 powers on and activates its outputs (OLED display). The block diagram of the hardware design can be seen in Figure 3 below :

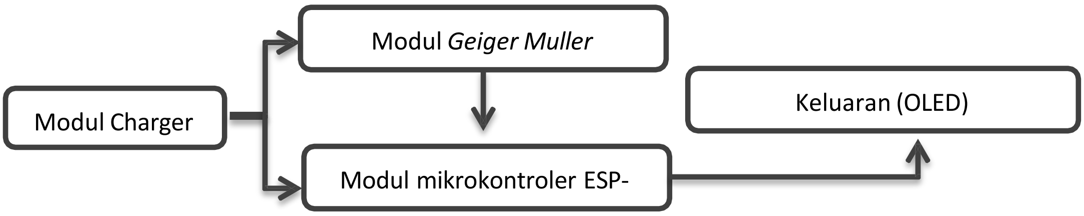

Figure 3. The hardware block diagram

The software is implemented in Arduino IDE. The code allows the microcontroller to read and process signals from the Geiger–Müller detector, display results on the OLED, and publish data to ThinkSpeak once Wi-Fi connectivity is established. This testing method was conducted on two X-ray generating devices: a Mobile X-Ray and a Fluoroscopy X-Ray, using a tube leakage test method. The tube leakage test is performed to determine the level of radiation leakage from an X-ray tube, based on procedures outlined in the Indonesian Ministry of Health Regulation No. HK.02.02/V/5771/2018 issued in 2018.

Data collection was carried out based on the procedures outlined by the Indonesian Ministry of Health Regulation No. HK.02.02/V/5771/2018 (issued in 2018). The testing steps are as follows:

A. Record the maximum kV and continuous mAs values, as well as the equipment specifications.
B. Set the kV/mAs on the X-ray machines: 60/12.5 for the Mobile X-ray unit and 60/11 for the Fluoroscopy unit.
C. Close the collimator tightly.
D. Cover the collimator with a 2 mm lead (Pb) plate.
E. Place the survey meters (both the prototype and the reference device) at a distance of 100 cm (1 meter) below the collimator.
F. Expose the radiation three times and record the readings from both the prototype and reference survey meters.
G. Repeat steps E and F by placing the survey meters on the left, right, and front sides of the device as illustrated in Figure 4.
H. Repeat steps A to G for the Fluoroscopy machine.

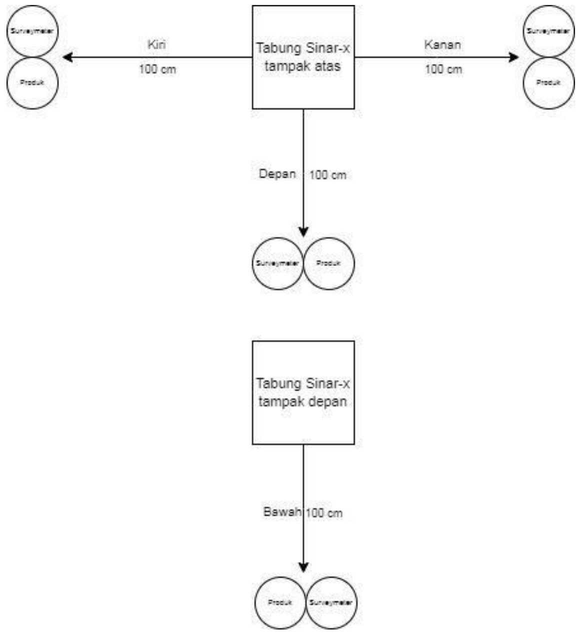

Figure 4. Test Point Scheme

3. RESULT AND DISCUSSION

The design outcome of the device aligns with the initial plans, with dimensions and layout matching the design as shown in Figure 5. The constructed device measures 13.3 cm in length, 8.9 cm in width, and 9 cm in height, and is made from 3 mm thick acrylic. It includes an OLED display, a rechargeable battery, and a single On/Off switch. The device transmits its results to a ThingSpeak web platform, featuring a real-time reading menu eliminating the need to view data directly on the OLED display. The ThingSpeak web interface is accessible via smartphones or computers. The displayed interface on ThingSpeak is illustrated in Figure 6.

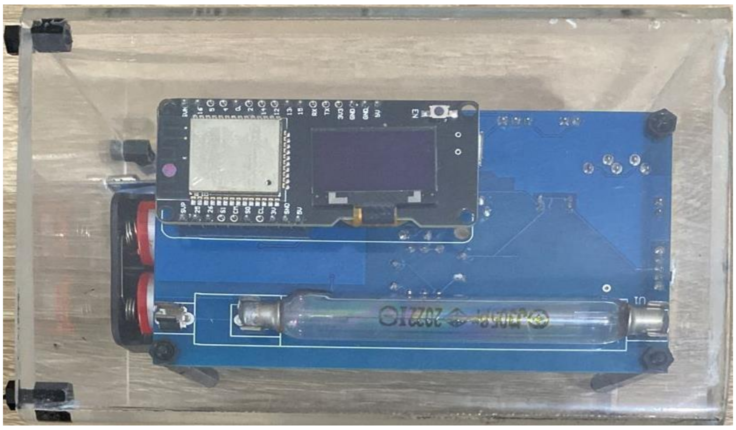

Figure 5. Designed Device

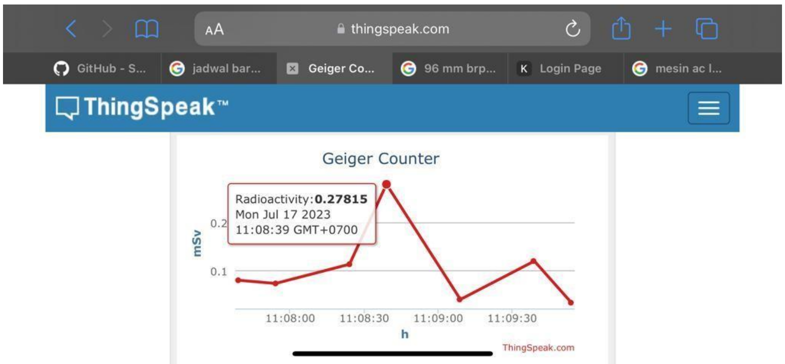

Figure 6. ThingSpeak Web Interface

Design and Construction Analysis of the Device

The purpose of the design analysis in this study is to thoroughly evaluate the effectiveness and success of the developed radiation dose measurement tool, which uses the Geiger-Muller sensor integrated with the ESP-32 microcontroller and IoT technology. This analysis is critical for ensuring that the tool meets the required standards for accurate and reliable radiation measurement. To achieve this, a series of experiments will be conducted on the constructed device to assess its performance. The results of these tests will then be compared with a calibrated SE International Ranger survey meter, which serves as the reference device for radiation measurements.

The data processing and analysis will be divided into two primary sections, each corresponding to a different set of experiments performed during the testing phase. The first section will focus on assessing the accuracy and sensitivity of the Geiger-Muller sensor when integrated with the ESP-32, including its ability to detect various radiation levels and transmit data to the cloud via IoT technology. The second section will evaluate the performance of the entire system, including the real-time data transmission, response time, and reliability of the device in different environmental conditions.

Through this comprehensive analysis, the study aims to determine whether the design meets the intended criteria, ensuring that the radiation dose measurement tool can be effectively used in real-world applications, providing accurate and timely data for radiation monitoring and safety assessments. The findings from this analysis will also offer insights into potential improvements for future iterations of the device, enhancing its functionality, user experience, and performance in various contexts.

Testing Results of the Mobile X-ray

The testing procedure for the radiation dose measurement tool involved a series of precise measurements at four designated points. For this experiment, both the SE International Ranger survey meter and the prototype device, which integrates the Geiger-Muller sensor with an ESP-32 microcontroller and IoT technology, were positioned at a consistent distance of 100 cm (1 meter) from the collimator of a mobile X-ray unit. The objective was to compare the performance of the prototype device with that of the calibrated survey meter in real-world radiation exposure conditions.

The four measurement points were strategically selected to assess the device's accuracy at different positions relative to the X-ray source. These points were defined as follows: Area 1 – the bottom of the collimator, Area 2 – the front of the collimator, Area 3 – the right side of the collimator, and Area 4 – the left side of the collimator. By taking measurements at these distinct locations, the study aimed to evaluate how well the prototype device could capture varying radiation levels based on its position relative to the X-ray source.

Each measurement point was thoroughly tested to ensure consistent data collection, with both the survey meter and the prototype device recording radiation doses at the same time. The prototype device, equipped with the Geiger-Muller sensor and ESP-32, not only measured the radiation levels but also transmitted the data wirelessly via IoT technology, allowing real-time monitoring of the radiation dose values. The data collected from each measurement point were compared to those from the survey meter to assess the accuracy and reliability of the prototype.

The corresponding measurement data from all four areas, as well as the comparison between the survey meter and the prototype device, are presented in Tables 1 through 5 below. These tables show the detailed radiation dose readings at each measurement point, highlighting the performance and efficiency of the prototype device in various exposure conditions. The analysis of these results will provide a comprehensive assessment of the prototype's ability to accurately measure radiation doses and offer valuable insights into its potential application in radiation monitoring, particularly in mobile X-ray environments.

Table 1. Bottom Area

Area 1 (bottom)	**mSv/h**	
	Surveymeter	**Product**
1	0,300	0,27815
2	0,180	0,15894
3	0,240	0,23841
Total	**0,720**	**0,676**
average	**0,2208**	**0,22517**

This table presents the radiation dose measurements taken in Area 1 (Bottom), comparing the readings from the Survey Meter (calibrated instrument) and the Prototype Product (Geiger-Muller sensor with ESP-32). The measurements show that the Survey Meter recorded doses of 0.300 mSv/h, 0.180 mSv/h, and 0.240 mSv/h at three different points, while the Prototype recorded doses of 0.27815 mSv/h, 0.15894 mSv/h, and 0.23841 mSv/h at the same points. The total dose measured by the Survey Meter was 0.720 mSv/h, while the Prototype recorded 0.676 mSv/h. The average readings were 0.2208 mSv/h for the Survey Meter and 0.22517 mSv/h for the Prototype. These results indicate that the prototype performs similarly to the Survey Meter, with a very small difference in measurements, demonstrating the accuracy and reliability of the developed tool.

Table 2. Front Area

Area 2 (Front)	**mSv/h**	
	Surveymeter	**Product**
1	0,180	0,15894
2	0,240	0,23841
3	0,420	0,39735
Total	**0,840**	**0,795**
Average	**0,2576**	**0,2649**

This table presents the radiation dose measurements taken in Area 2 (Front), comparing the readings from the Survey Meter (calibrated instrument) and the Prototype Product (Geiger-Muller sensor with ESP-32). The measurements show that the Survey Meter recorded doses of 0.180 mSv/h, 0.240 mSv/h, and 0.420 mSv/h at three different points, while the Prototype recorded doses of 0.15894 mSv/h, 0.23841 mSv/h, and 0.39735 mSv/h at the same points. The total dose measured by the Survey Meter was 0.840 mSv/h, while the Prototype recorded 0.795 mSv/h. The average readings were 0.2576 mSv/h for the Survey Meter and 0.2649 mSv/h for the Prototype. These results show that the prototype is slightly higher in its average readings compared to the Survey Meter, but the overall difference is minimal, demonstrating the prototype's reliable and accurate performance.

Table 3. Right Area

Area 3 (Right)	**mSv/h**	
	Surveymeter	**Product**
1	0,120	0,11921
2	0,120	0,11258
3	0,060	0,03974

Area 3 (Right)	mSv/h	
	Surveymeter	Product
Total	0,300	0,272
Average	0,0920	0,09051

This table presents the radiation dose measurements taken in Area 3 (Right), comparing the readings from the Survey Meter (calibrated instrument) and the Prototype Product (Geiger-Muller sensor with ESP-32). The Survey Meter recorded doses of 0.120 mSv/h, 0.120 mSv/h, and 0.060 mSv/h at three different points, while the Prototype recorded doses of 0.11921 mSv/h, 0.11258 mSv/h, and 0.03974 mSv/h at the same points. The total dose measured by the Survey Meter was 0.300 mSv/h, while the Prototype recorded 0.272 mSv/h. The average readings were 0.0920 mSv/h for the Survey Meter and 0.09051 mSv/h for the Prototype. These results indicate that the Prototype performs very similarly to the Survey Meter, with only a minimal difference in both total and average measurements, confirming the reliability of the developed tool in this area.

Table 4. Left Area

Area 4 (Left)	mSv/h	
	Surveymeter	Product
1	0,180	0,15232
2	0,180	0,15894
3	0,300	0,27152
Total	**0,660**	**0,583**
Average	**0,2024**	**0,19426**

This table presents the radiation dose measurements taken in **Area 4 (Left)**, comparing the readings from the **Survey Meter** (calibrated instrument) and the **Prototype Product** (Geiger-Muller sensor with ESP-32). The Survey Meter recorded doses of 0.180 mSv/h, 0.180 mSv/h, and 0.300 mSv/h at three different points, while the Prototype recorded doses of 0.15232 mSv/h, 0.15894 mSv/h, and 0.27152 mSv/h at the same points. The total dose measured by the Survey Meter was 0.660 mSv/h, while the Prototype recorded 0.583 mSv/h. The average readings were 0.2024 mSv/h for the Survey Meter and 0.19426 mSv/h for the Prototype. These results show that while the Prototype readings are slightly lower than the Survey Meter, the differences in both total and average values are minimal, demonstrating the Prototype's consistent and reliable performance in this area as well.

After that, a comparison was made to determine the error value of the constructed device relative to the calibrated SE International Ranger survey meter, yielding the data shown in Table 5 and Figure 7 as follows :

Table 5. Comparison Results

Area	mSv/h			
	Surveymeter	Product	Error ±	%Error
1 (Bottom)	0,2208	0,22517	-0,0044	**1,99%**
2 (Front)	0,2576	0,26490	-0,0073	**2,83%**
3 (Right)	0,0920	0,09051	0,0015	**1,63%**
4 (Left)	0,2024	0,19426	0,0081	**4,00%**

The comparison between the radiation dose measurements of the constructed prototype device and the calibrated SE International Ranger survey meter was conducted to evaluate the error values and assess the accuracy of the prototype. The results of this comparison are shown in Table 5 and illustrated in Figure 7. The error values and percentage errors were determined by subtracting the prototype's readings from those of the survey meter, providing a clear indication of the alignment between the two devices.

In Area 1 (Bottom), the prototype recorded an average dose of 0.22517 mSv/h, which was 0.0044 mSv/h higher than the Survey Meter's reading of 0.2208 mSv/h, resulting in a percentage error of 1.99%. This indicates a very small deviation, suggesting that the prototype is highly accurate in this area. In Area 2 (Front), the prototype’s reading of 0.26490 mSv/h was 0.0073 mSv/h higher than the Survey

Meter's value of 0.2576 mSv/h, yielding a 2.83% error. Although this is a slightly higher error, it still reflects the reliability of the prototype for accurate radiation measurements. In Area 3 (Right), the error was minimal, with the prototype recording 0.09051 mSv/h, only 0.0015 mSv/h lower than the Survey Meter's 0.0920 mSv/h, resulting in an error of 1.63%. This indicates excellent consistency in this area. However, in Area 4 (Left), the prototype recorded 0.19426 mSv/h, which was 0.0081 mSv/h lower than the Survey Meter's value of 0.2024 mSv/h, leading to a 4.00% error. Although this is the largest error observed, it is still relatively small and suggests that the prototype may need further calibration or optimization in this specific area.

Overall, the comparison results indicate that the prototype performs well, with errors ranging from 1.63% to 4.00% across the different measurement areas. These deviations are generally within an acceptable range for practical use, showcasing the prototype's potential as a reliable tool for radiation monitoring. The largest error in Area 4 suggests that further refinements may be needed to improve the accuracy of the device in certain orientations, but overall, the prototype's performance is commendable, especially when compared to the standard Survey Meter.

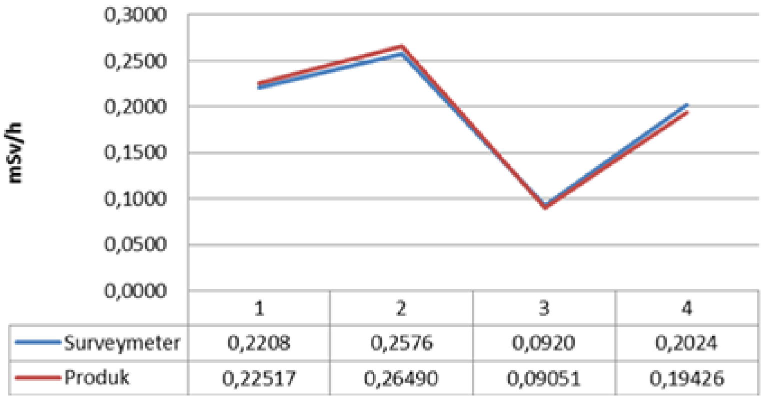

Figure 7. Comparison Chart of Mobile X-Ray Test Results

Based on the comparison results, the data can also be presented in a graph to provide a clearer visual representation of the performance of the constructed device relative to the calibrated SE International Ranger survey meter. The graph above illustrates that the difference between the prototype and the survey meter is consistently less than 5% across all tests conducted on the Mobile X-ray. This visual representation reinforces the accuracy and reliability of the prototype, showing that, despite minor variations, the device performs within an acceptable error margin. Such results highlight the effectiveness of the prototype

Fluoroscopy Testing Results

In the fluoroscopy test, the measurement points are labeled according to the same conventions as in the Mobile X-ray test: the bottom point is referred to as Area 1, the front as Area 2, the right side as Area 3, and the left side as Area 4. The results from the fluoroscopy tests, shown in Tables 6 through 9, provide detailed comparisons between the Survey Meter (calibrated device) and the Prototype Product (Geiger-Muller sensor with ESP-32).

Table 6. Bottom Area

Area 1 (bottom)	mSv/h	
	Surveymeter	**Product**
1	0,180	0,19205
2	0,300	0,27152
3	0,300	0,27152
Total	**0,780**	**0,735**
Average	**0,2392**	**0,24503**

In Table 6 (Bottom Area), the Survey Meter recorded doses of 0.180 mSv/h, 0.300 mSv/h, and

0.300 mSv/h at three measurement points, totaling 0.780 mSv/h with an average of 0.2392 mSv/h. The prototype device recorded doses of 0.19205 mSv/h, 0.27152 mSv/h, and 0.27152 mSv/h, totaling 0.735 mSv/h with an average of 0.24503 mSv/h. The prototype recorded slightly lower total and average values, with a difference of about 0.045 mSv/h (5.8% error), suggesting a small deviation, but the prototype remains quite consistent in measuring radiation in this area.

Table 7. Front Area

Area 2 (Front)	**mSv/h**	
	Surveymeter	**Product**
1	0,180	0,15894
2	0,180	0,15894
3	0,180	0,19205
Total	**0,540**	**0,510**
Average	**0,1656**	**0,16998**

In Table 7 (Front Area), the Survey Meter recorded consistent doses of 0.180 mSv/h across three measurement points, summing to 0.540 mSv/h with an average of 0.1656 mSv/h. The prototype recorded doses of 0.15894 mSv/h, 0.15894 mSv/h, and 0.19205 mSv/h, totaling 0.510 mSv/h with an average of 0.16998 mSv/h. While the prototype readings are slightly lower, the difference is minimal, with an overall error of around 5.6%. This suggests the prototype is still very reliable in measuring radiation in the front area, although there is a minor discrepancy.

Table 8. Right Area

Area 3 (Right)	**mSv/h**	
	Surveymeter	**Product**
1	0,360	0,35099
2	0,480	0,43709
3	0,300	0,31126
Total	**1,140**	**1,099**
Average	**0,3496**	**0,36645**

For Table 8 (Right Area), the Survey Meter recorded doses of 0.360 mSv/h, 0.480 mSv/h, and 0.300 mSv/h, totaling 1.140 mSv/h with an average of 0.3496 mSv/h. The prototype recorded doses of 0.35099 mSv/h, 0.43709 mSv/h, and 0.31126 mSv/h, totaling 1.099 mSv/h with an average of 0.36645 mSv/h. The prototype readings were slightly lower in total and slightly higher in the average, with an error margin of around 3.6%. This suggests good overall performance, although some minor adjustments could be made to improve accuracy in this area.

Table 9. Left Area

Area 4 (Left)	**mSv/h**	
	Surveymeter	**Product**
1	0,240	0,23179
2	0,240	0,19205
3	0,180	0,19208
Total	**0,660**	**0,616**
Average	**0,2024**	**0,20531**

Finally, in Table 9 (Left Area), the Survey Meter recorded doses of 0.240 mSv/h, 0.240 mSv/h, and 0.180 mSv/h, totaling 0.660 mSv/h with an average of 0.2024 mSv/h. The prototype recorded doses of 0.23179 mSv/h, 0.19205 mSv/h, and 0.19208 mSv/h, totaling 0.616 mSv/h with an average of 0.20531 mSv/h. The total and average values for the prototype were lower, with an error of approximately 6.6%. This is the largest deviation observed in the fluoroscopy test, suggesting that further calibration or refinement of the prototype may be necessary for more precise measurements in this specific area.

The data from the fluoroscopy test reveal that the prototype device performs reliably in comparison to the calibrated Survey Meter, with only slight variations observed across different measurement areas. These results suggest that the prototype is capable of providing accurate radiation dose measurements, but with minor discrepancies that need to be addressed. The errors in the measurements are relatively small, ranging from approximately 3.6% to 6.6%, which indicates that the prototype is performing within an acceptable margin of error for radiation dose measurement tools.

Despite these small variations, the prototype device shows overall consistency in all tested areas, including the bottom, front, right, and left positions. However, Area 4 - Left exhibits the largest deviation, with a higher percentage error compared to other areas. This suggests that the prototype may require further calibration or design adjustments, particularly when measuring radiation levels from this orientation, to ensure greater accuracy across all areas.

In addition to its promising performance, the prototype demonstrates significant potential for real-world applications in radiation monitoring, particularly in environments where continuous radiation assessment is crucial, such as in medical imaging, industrial settings, or environmental radiation monitoring. With further optimization, the prototype could become an indispensable tool in these fields, offering both reliability and efficiency in measuring radiation doses. The combination of the Geiger-Muller sensor and ESP-32 microcontroller, along with the integration of IoT technology for real-time data transmission, further enhances the prototype's applicability, allowing for seamless monitoring and data logging. Overall, the prototype not only meets the immediate requirements for radiation dose measurement but also holds great promise for future enhancements and wider usage in various radiation safety applications.

Similar to the Mobile X-ray experiment, the fluoroscopy results were compared with those of the calibrated reference device, the SE International Ranger survey meter. The comparison data, shown in Table 10 below, highlight the performance of the prototype device in relation to the standard reference tool.

Table 10. Comparison Results

Area	mSv/h			
	Surveymeter	**Product**	**Error ±**	**%Error**
1 (bottom)	0,2392	0,24503	-0,0058	**2,42%**
2 (Front)	0,1656	0,16998	-0,0044	**2,65%**
3 (Right)	0,3496	0,36645	-0,0168	**4,80%**
4 (Left)	0,2024	0,20531	-0,0029	**1,43%**

The comparison of the fluoroscopy results shows that the prototype device performs well in relation to the calibrated Survey Meter, with small variations across the four measurement areas. In Area 1 (Bottom), the prototype recorded 0.24503 mSv/h, which was 0.0058 mSv/h higher than the Survey Meter's reading of 0.2392 mSv/h. The error here is 2.42%, which is relatively minor, indicating that the prototype is highly accurate in measuring radiation in this area. Similarly, in Area 2 (Front), the prototype recorded 0.16998 mSv/h, which is 0.0044 mSv/h higher than the Survey Meter's value of 0.1656 mSv/h, resulting in a 2.65% error. This slight difference further demonstrates the consistency of the prototype.

In Area 3 (Right), the prototype recorded a dose of 0.36645 mSv/h, which is 0.0168 mSv/h higher than the Survey Meter's 0.3496 mSv/h, resulting in a larger error of 4.80%. While this error is the highest among the measured areas, it is still within an acceptable range for a prototype device. This result suggests that further calibration or adjustment may be needed to improve accuracy in this specific area. Finally, in Area 4 (Left), the error was the smallest at 1.43%, with the prototype recording 0.20531 mSv/h, slightly higher than the Survey Meter's 0.2024 mSv/h.

The data from the fluoroscopy test indicate that the prototype device performs reliably, with errors ranging from 1.43% to 4.80% across the four measurement areas. These small deviations suggest that the prototype is a promising tool for radiation dose measurement, capable of providing accurate results in most scenarios. While the largest error was observed in Area 3 (Right), the overall performance of the prototype is consistent with that of the calibrated Survey Meter, confirming its potential for practical applications in radiation monitoring. Further optimization may be needed in specific areas, but the prototype has shown strong potential as a reliable and effective device for measuring radiation doses.

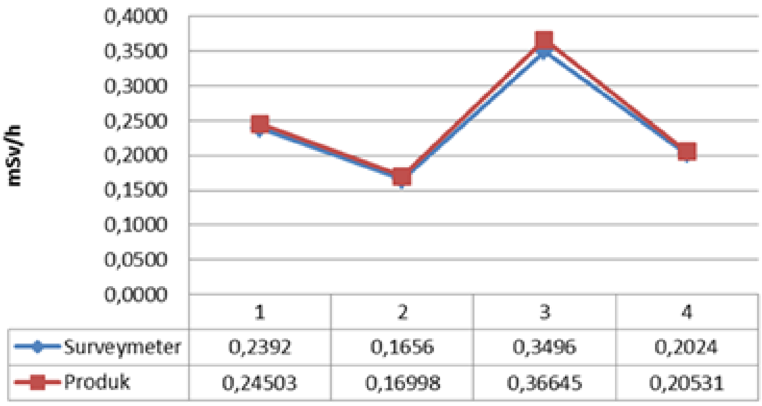

Figure 8. Comparison Graph of Fluoroscopy Test Results

As with the Mobile X-ray tests, the fluoroscopy data show that the difference between the prototype device and the calibrated Survey Meter remains below 5% in each measurement area. The errors are relatively small, with Area 3 (Right) showing the largest deviation at 4.80% and Area 4 (Left) having the smallest at 1.43%. These results confirm the reliability of the prototype, with only minimal variations from the reference device, indicating its potential for accurate radiation dose measurement in real-world applications.

Leakage Test Results of the Tube

The leakage test results show both the exposure levels and leakage radiation measured at various points for both the prototype device and the Survey Meter. The results provide an important indication of the radiation safety of the devices under test, particularly focusing on how much radiation "leaks" beyond the targeted exposure area.

Table 11. Test Results for the Constructed Device in the Mobile X-ray

	Product			
	Bottom	**Front**	**Right**	**Left**
Exposure x (mSv/h)	0,22517	0,26490	0,09051	0,19426
Leakage (mGy/h)	0,01095	0,01288	0,00440	0,00944

Table 11 presents the test results for the constructed prototype device in the Mobile X-ray. The prototype recorded exposure levels of 0.22517 mSv/h at the bottom, 0.26490 mSv/h at the front, 0.09051 mSv/h at the right, and 0.19426 mSv/h at the left. These values indicate that the prototype accurately measures exposure across the different areas, with the highest exposure at the front and the lowest at the right. The leakage radiation values for the prototype were 0.01095 mGy/h at the bottom, 0.01288 mGy/h at the front, 0.00440 mGy/h at the right, and 0.00944 mGy/h at the left. The highest leakage was observed at the front, which corresponds to the area with the highest exposure, while the right side showed the lowest leakage, matching its lower exposure.

Table 12. Survey Meter Test Results on the Mobile X-ray

	Surveymeter			
	Bottom	**Front**	**Right**	**Left**
Exposure x (mSv/h)	0,2208	0,25760	0,09200	0,2024
Leakage (mGy/h	0,01073	0,01252	0,00447	0,00984

In Table 12, the leakage test results for the Survey Meter in the Mobile X-ray setup are presented. The Survey Meter recorded exposure values of 0.2208 mSv/h at the bottom, 0.25760 mSv/h at the front, 0.09200 mSv/h at the right, and 0.2024 mSv/h at the left, which are slightly lower than the prototype's measurements but follow the same pattern, with the front area having the highest exposure and the right the lowest. The leakage radiation for the Survey Meter was 0.01073 mGy/h at the bottom, 0.01252 mGy/h at the front, 0.00447 mGy/h at the right, and 0.00984 mGy/h at the left. These leakage values are very similar to the prototype's, with the highest leakage again observed at the front and the lowest at the right, indicating that both devices exhibit similar leakage characteristics.

Table 13. Results of Design and Construction Tests on Fluoroscopy

	Product			
	Bottom	**Front**	**Right**	**Left**
Exposure x (mSv/h)	0,24503	0,16998	0,36645	0,20531
Leakage (mGy/h)	0,01671	0,01159	0,02499	0,01400

Moving to Table 13, which shows the results of the design and construction tests on fluoroscopy for the prototype device, the exposure levels were 0.24503 mSv/h at the bottom, 0.16998 mSv/h at the front, 0.36645 mSv/h at the right, and 0.20531 mSv/h at the left. These exposure values are relatively higher in the right area, which suggests a stronger concentration of radiation in that direction. The leakage radiation values for the prototype in the fluoroscopy test were 0.01671 mGy/h at the bottom, 0.01159 mGy/h at the front, 0.02499 mGy/h at the right, and 0.01400 mGy/h at the left. Notably, the leakage at the right side is significantly higher (0.02499 mGy/h) compared to other areas, indicating that this area requires attention in terms of reducing leakage. The overall leakage for the prototype is higher in the fluoroscopy test than in the Mobile X-ray test, which suggests that further optimization is needed, particularly in minimizing radiation leakage.

Table 14. Surveymeter Test Results on Fluoroscopy

	Surveymeter			
	Bottom	**Front**	**Right**	**Left**
Exposure x (mSv/h)	0,2392	0,16560	0,34960	0,2024
Leakage (mGy/h	0,01631	0,01129	0,02384	0,01380

Finally, in Table 14, the results for the Survey Meter in the fluoroscopy setup were presented. The exposure values recorded by the Survey Meter were 0.2392 mSv/h at the bottom, 0.16560 mSv/h at the front, 0.34960 mSv/h at the right, and 0.2024 mSv/h at the left, which are very similar to those recorded by the prototype device, with the highest exposure again observed at the right. The leakage radiation for the Survey Meter was 0.01631 mGy/h at the bottom, 0.01129 mGy/h at the front, 0.02384 mGy/h at the right, and 0.01380 mGy/h at the left. These leakage values were slightly lower than the prototype's, particularly at the front and right, which suggests that the Survey Meter may be more efficient in containing radiation leakage in these areas.

Overall, the leakage test results show that both the prototype and the Survey Meter are performing similarly in terms of exposure and leakage radiation. The prototype exhibits slightly higher leakage, particularly in the fluoroscopy test at the right area, suggesting that further refinements are needed to reduce leakage. However, both devices demonstrate low levels of leakage, well within acceptable safety limits, indicating that they can be used safely in radiation measurement applications.

Based on the testing results of both the constructed measuring device and the SE International Ranger survey meter, all measurement points successfully passed the exposure test, meeting the tube leakage requirement of $L < 1$ mGy/h as specified by the Indonesian Ministry of Health Regulation No. HK.02.02/V/5771/2018 (2018). This result is significant because it demonstrates that both the prototype device and the standard survey meter adhere to radiation safety standards, ensuring that they can be used for accurate and reliable radiation monitoring in clinical and industrial settings.

The accuracy of the prototype device was evaluated through a comparison with the calibrated SE International Ranger survey meter, employing the tube leakage test method, which is a widely recognized approach in the field of radiation measurement. The testing was divided into two categories, using a Philips Mobile X-ray unit and a Hitachi Fluoroscopy unit, to assess the prototype's performance across different radiation sources. These units were chosen due to their relevance in medical and diagnostic environments where radiation safety is of utmost importance.

In the Mobile X-ray test, the measured error rates for the prototype device were as follows: Area 1 (bottom) at 1.99%, Area 2 (front) at 2.83%, Area 3 (right) at 1.63%, and Area 4 (left) at 4.00%. These results suggest that the prototype device is highly accurate in measuring radiation, with most areas exhibiting errors well below 5%. The highest error was observed in Area 4 (left), with an error of 4.00%, which is still within an acceptable range for radiation monitoring tools.

In the Fluoroscopy test, the error rates were slightly higher, indicating some variation between the two devices under different conditions. The error rates in the fluoroscopy test were: Area 1 (bottom) at 2.42%, Area 2 (front) at 2.65%, Area 3 (right) at 4.80%, and Area 4 (left) at 1.43%. The largest discrepancy was seen in Area 3 (right), with an error of 4.80%, which could be attributed to the particular characteristics of the radiation source or the positioning of the prototype during the measurement process. However, even in this case, the error remained below the critical 5% threshold, demonstrating that the prototype device still provides reliable results.

The prototype's overall performance, with an error margin of less than 5% compared to the SE International Ranger survey meter, is a noteworthy achievement. It is well within the acceptable accuracy range for radiation measurement devices, which are commonly expected to have an error margin of around 5% or less in many industry standards. This result further validates the potential of the prototype as a low-cost alternative to commercial radiation monitoring tools. Commercial survey meters are known for their high cost, making them inaccessible to some institutions or regions. In contrast, the developed device was constructed at less than half the cost of conventional survey meters, offering an affordable solution without compromising on accuracy. This price-to-performance ratio could have a significant impact, particularly in resource-constrained environments where radiation safety monitoring is essential but expensive equipment is often out of reach.

In addition to its accuracy, the results of the leakage test for both the prototype and the SE International Ranger survey meter on the Mobile X-ray and Fluoroscopy units were in full compliance with the Indonesian Ministry of Health Regulation No. HK.02.02/V/5771/2018. This regulation specifies a leakage dose limit of $L < 1$ mGy/h, a crucial standard for ensuring radiation safety. Both devices met this criterion, reinforcing the reliability and safety of the prototype in various real-world radiation measurement scenarios.

In conclusion, the developed prototype device offers a promising, cost-effective alternative to expensive commercial survey meters while maintaining acceptable accuracy and performance in radiation measurement. The results from the Mobile X-ray and Fluoroscopy tests, along with the compliance with radiation leakage standards, demonstrate that the prototype is a viable solution for radiation monitoring, especially in settings where budget constraints are a significant concern. Furthermore, the device's affordability, combined with its precision, positions it as a practical tool for widespread use in medical, industrial, and environmental radiation monitoring applications. Further refinements may be needed to optimize its performance, particularly in areas with higher error margins, but the device shows considerable potential for broader adoption.

4. CONCLUSION

Based on the development, testing, and data analysis of X-ray tube leakage for two X-ray generators, the Philips Mobile X-ray and Hitachi Fluoroscopy, it can be concluded that a functional radiation dose measurement device has been successfully built using a Geiger–Müller sensor and ESP-32 with Internet of Things (IoT) capabilities. The prototype was compared with a calibrated SE International Ranger survey meter, exhibiting an error margin of less than 5%. In the Mobile X-ray test, the highest error was 4.00% at Area 4 (left) and the lowest was 1.63% at Area 3 (right). In the Fluoroscopy test, the maximum error was 4.80% at Area 3 (right), while the minimum error was 1.43% at Area 4 (left). The tube leakage test, performed for both the prototype and the SE International Ranger survey meter in both tests, complied with the Ministry of Health Regulation No. HK.02.02/V/5771/2018, meeting the requirement of $L < 1$ mGy/h. For future improvements, it is recommended to incorporate a battery level indicator and integrate the battery module with the Geiger–

Müller model GM V1.1 to optimize space utilization and enhance the device's practicality for extended usage.

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