Smart X-Ray Geiger Data Logger: An Integrated System for Detection, Control, and Dose Evaluation

Lhoucine Ben Youssef[1], Hilal Drissi[2], Abdelmajid Bybi[3], El Ayachi Chater[4]
Mohammed V University in Rabat, Higher School of Technology of Salé, LASTIMI, Salé, Morocco[1, 2, 4]
Mohammed V University in Rabat, Higher School of Technology of Salé, MEAT, Salé, Morocco[3]

***Abstract*—X-ray dosimetry practices are guided by international standards and regulatory agencies to ensure the safety of patients, radiation workers, and the general public. This paper introduces the Smart X-ray Geiger Data Logger, a comprehensive system designed to enhance radiation safety through integrated detection, control, and dose evaluation. This study is based on the M4011 Geiger-Müller tube, exploiting ionization effects to measure radiation doses accurately. The system features an advanced algorithm for real-time exposure risk assessment, ensuring adherence to safety limits during medical procedures. Equipped with Wi-Fi connectivity, the device facilitates seamless data transmission and integration with centralized databases for comprehensive exposure monitoring and historical data analysis. The MQTT protocol is utilized for secure and efficient data transmission, ensuring the protection of sensitive information. A user-friendly interface provides instant feedback on radiation levels, cumulative doses, and procedural safety, supported by visual indicators and auditory alarms for immediate alerts. Experimental validation demonstrates the system's reliability in various settings, confirming its utility in optimizing radiation protection strategies and fostering safer environments in the healthcare field.**

Keywords*—*X-rays; radiation dose; radiation safety; exposure risk assessment; Geiger-Müller tube; medical imaging; real-time monitoring; smart devices

I. INTRODUCTION

X-rays are a form of electromagnetic radiation with wavelengths shorter than visible light. They were discovered by Wilhelm Conrad Roentgen in 1895. X-rays have the ability to penetrate most substances, and they are widely used in medical imaging, industry, and scientific research. In medical applications, X-rays are commonly used for imaging bones and internal structures, helping diagnose and monitor various medical conditions [1-3].

X-ray dosimetry involves the measurement and assessment of the absorbed dose of X-ray radiation received by human tissue. The primary goal is to quantify the amount of energy deposited in a specific area, which is crucial for various applications, including medical imaging and radiation therapy [4].

Ongoing research aims to develop new dosimetry techniques, materials, and technologies to enhance accuracy, sensitivity, and efficiency in measuring X-ray doses. To illustrate, Fum et al. [5] worked on Monte Carlo (MC) methods in fluoroscopy-guided interventions for clinical dosimetry, with potential advancements in dynamic, deformable phantoms and automated image-based alignment for enhanced patient specificity. To efficiently and expeditiously assess X, γ, and neutron radiation fields concurrently, Yang et al. [6], developed a portable multifunction radiation detection system employing LaBr3(Ce) crystal, LASO neutron detector, and high-range GM counter, data measured transmitted to a PC through a USB interface. Johnson et al. [7] survey cutting-edge approaches for X-ray dose detection, such as semiconductor detectors and digital dosimeters, underscoring their enhanced precision and quicker response times compared to conventional techniques. Furthermore, Garcia et al. [8] assess the implementation of automated X-ray dose tracking systems in hospital settings, revealing a 25% reduction in incidents of excessive radiation exposure among patients. Brown et al. [9] explores advanced dosimetry methods like real-time dosimeters and patient dose mapping, which significantly bolster X-ray imaging safety, resulting in a 40% enhancement in radiation dose control. Moreover, Thomas et al. [10] spotlight recent advancements in X-ray dose monitoring technologies, including wearable dosimeters and machine learning algorithms, which collectively lowered radiation exposure by 20% in clinical environments.

Excessive exposure to X-rays poses significant health risks, including radiation burns, radiation sickness, and an increased risk of cancer. As X-ray technology is widely used in medical imaging, it is crucial to monitor and control the radiation dose received by individuals to ensure their safety. Traditional methods of measuring X-ray exposure can be inadequate or cumbersome, leading to the necessity for a more efficient, accurate, and user-friendly solution. In this context, Wilson et al. [11] investigate the development of portable X-ray dose detectors utilizing microelectromechanical systems (MEMS), demonstrating their high accuracy and ease of use in clinical trials. On the other hand, Smith et al. [12] delve into recent advancements in real-time monitoring of X-ray doses during radiological procedures, utilizing advanced sensor arrays to achieve a 30% decrease in patient radiation exposure. Meanwhile, Robinson et al. [13] analyze the complexities of real-time X-ray dose management through case studies, proposing solutions that integrate dose monitoring systems to enhance safety compliance by 50%. Martinez et al. [14] explore the integration of artificial intelligence to enhance X-ray dose detection and monitoring, revealing that AI algorithms enhance detection accuracy by 25% and reduce false positives by 30%. Lastly, Silva et al. [15] describe the development of low-cost X-ray equipment including an X-ray machine, a Geiger detector, and a goniometer, aimed at facilitating accessible study and experimentation in X-ray physics.

To address the critical need for real-time, precise monitoring of X-ray exposure, we developed the Smart X-ray Geiger Data Logger. This device can provide immediate feedback on radiation doses including instant and cumulative dose, enabling users to take timely actions to minimize exposure. Otherwise, our solution is particularly valuable in medical environments, ensuring that patients and healthcare workers are not subjected to unnecessary radiation. Additionally, the Smart X-ray Geiger Data Logger is a handheld device used to detect, control and evaluate X-ray doses. It operates based on the ionization effect produced when radiation interacts with a gas inside the Geiger-Muller tube. By employing advanced algorithm for exposure risk assessment, the Smart X-ray Geiger Data Logger can improve radiation safety management, protecting health and enhancing overall safety standards.

This paper is structured into two main sections: The first section comprehensively explores the materials and methods employed in the study, detailing the experimental setup, equipment specifications, and data collection procedures. The second section is dedicated to presenting and discussing the results obtained from the experiments. It analyzes the findings in the context of existing solutions, discusses implications for the field, and explores potential avenues for further research.

II. Materials and Methods

A. X-Ray Doses

Dosimeters are employed in medical field to monitor personnel radiation exposure during diagnostic X-ray procedures and in occupational application to ensure that radiation workers are not exposed to harmful levels of radiation. To evaluate the risk of excessive dose absorption, we based on the effective dose of the body, which is a measure used in radiology to estimate the overall risk of harm from ionizing radiation exposure. It takes into account the different sensitivities of various tissues and organs in the body to radiation.

The calculation of effective dose involves three main steps: first, determining organ and tissue weighting factors (Table I), which reflect the varying sensitivities of different tissues and organs to radiation and are set by organizations like the International Commission on Radiological Protection [16]. Second, calculating the absorbed dose, the energy deposited per unit mass in a specific organ or tissue, measured in gray, based on radiation type, energy, and exposure conditions. Finally, the effective dose is obtained by multiplying the absorbed dose in each organ or tissue by its respective weighting factor and summing these values across all exposed organs and tissues.

It's important to note that the effective dose is an estimate of the overall risk and not a direct measure of the biological effect on an individual. It is a useful concept for comparing and managing radiation risks in different exposure scenarios. Absorbed dose is the amount of energy imparted by ionizing radiation per unit mass of irradiated material. It is measured in gray (Gy) in the International System of Units (SI). Absorbed dose can be calculated using dosimeters, devices specifically designed to measure the energy deposited by X-rays in a given material. However, there are various types of dosimeters used in X-ray dosimetry, including ionization chambers, thermoluminescent dosimeters (TLDs), semiconductor detectors, and film badges.

TABLE I. Organ and Tissues Weighting Factor

Tissue or Organ	ICRP 103
Gonads	0.08
Lung	0.12
Colon	0.12
Stomach	0.12
Breast	0.12
Bladder	0.04
Liver	0.04
Esophagus	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Brain	0.01

The principal function of an X-ray dosimeter based on ionization chambers is to measure and quantify the ionizing radiation exposure from X-rays. Ionization chambers operate by detecting the electrical charge produced when X-ray photons ionize the gas molecules within the chamber [17-19]. Likewise, TLD dosimeters play a crucial role in assessing radiation exposure by utilizing the thermoluminescent properties of certain materials to measure the amount of energy absorbed from ionizing radiation [20-25]. In other hand, Semiconductor detectors for X-rays serve as key tools for detecting and measuring ionizing radiation in various applications [26-29], their high sensitivity, spatial resolution, and fast response time make them valuable in diverse applications, including medical imaging, industrial inspection, and radiation monitoring. Finally, X-ray dosimeters based on film badges are practical tools for monitoring ionizing radiation exposure, offering wearable, cost-effective, and dose-history recording solutions for individuals working in environments where X-rays are present [30-32].

In our case, we used the ionization chamber M4011 Geiger-Müller Tube shown in Fig. 1. The interaction of X-ray photons with gas, leading to the formation of ion pairs (positive and negative charges) within the chamber. An electric field applied within the ionization chamber separates these ion pairs, and the resulting electric current or charge is quantified. This current's magnitude is directly proportional to the degree of ionization, which correlates with the radiation dose. Converting the measured charge into a radiation dose, typically expressed in Sieverts (Sv), enables a quantitative evaluation of absorbed radiation. Renowned for their precision and reliability across a broad spectrum of energies, ionization chambers find application in diverse fields such as medicine, industry, and research.

Fig. 1. M4011 Geiger-Müller tube.

B. X-Ray Doses Detection and Assessment

Dose quantities, such as entrance surface dose (ESD) and organ or effective dose, are often used to assess and report radiation exposure in medical imaging. To effectively measure, display, control, and monitor these doses, we have developed the Smart X-ray Geiger Data Logger, as shown in Fig. 2.

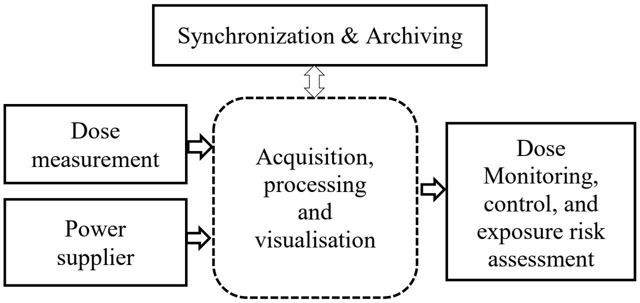

Fig. 2. Smart X-ray Geiger Data Logger for measurement and monitoring of X-ray doses in medical imaging.

The Smart X-ray Geiger Data Logger is an innovative device designed for the collection, control, monitoring, and evaluation of X-ray doses. Its primary purpose is to ensure the safety and protection of individuals from excessive X-ray exposure, thereby reducing the risk of radiation-induced diseases such as cancer.

The device is equipped with its own battery and power adapter, ensuring continuous operation even in the absence of an external power source. It includes memory storage for dose data, allowing offline access to historical exposure information. Built-in Wi-Fi capability allows the device to connect to a database for data acquisition and retrieval. The MQTT protocol is utilized for secure and efficient data transmission, ensuring the protection of sensitive information. An auditory alarm and LED indicators are activated when the absorbed dose exceeds predefined safety limits, providing immediate alerts to the user. Additionally, the device features a specialized algorithm for exposure risk assessment. Before proceeding with a new examination, the algorithm evaluates the risk based on the reference dose for the upcoming exam and the cumulative dose previously received. If the total dose does not exceed the safety limit, the device grants permission for the new exam. Otherwise, it warns the user of the potential risks and suggests alternative procedures.

The Smart X-ray Geiger Data Logger is a versatile tool that empowers individuals to continuously monitor and control their X-ray exposure, ensuring their safety. In medical settings, it helps radiology departments and doctors in making informed decisions about X-ray examinations, enhancing patient safety. Biomedical technicians and engineers benefit from using the device during the installation, maintenance, checkup, startup, and calibration of X-ray equipment, as it helps control their exposure to scattered radiation. Radiology technicians also find it invaluable for managing their radiation exposure during daily operations. The primary objectives of the Smart X-ray Geiger Data Logger are to validate the necessity of X-ray doses, avoid unnecessary exposure, safeguard individuals from excessive radiation, prevent radiation-related diseases, and assist healthcare professionals in optimizing patient care.

In the pursuit of measuring values, our preference leaned towards the M4011 Geiger- Müller tube, chosen for its specific attributes (380-450V, 25 pulse/minutes) [33]. This selection aligns harmoniously with the requirements of our solution. As for the power supply, we integrated a lithium battery featuring 3300 mAh and 3.7V.

Fig. 3 illustrates the diagram of our device and the connections between its various components. At the heart of our system lies the ESP32 board, assuming a central role in managing data acquisition, executing algorithmic processing, and presenting results on the display. Beyond these functions, it acts as a crucial facilitator for seamless communication among the diverse elements within our system. Boasting a robust 32-bit dual-core microcontroller that operates at clock frequencies of up to 240 MHz, the ESP32 board distinguishes itself with its integrated Wi-Fi and Bluetooth capabilities, making it highly suitable for a wide array of IoT (Internet of Things) applications. These boards exhibit varying amounts of Flash memory for program storage and RAM for data storage, the specific sizes of which depend on the model. Noteworthy is the ESP32's intentional design for power efficiency, supporting a range of power modes to optimize energy consumption, particularly beneficial for battery-operated devices [34].

The RadiationD V1.1 board is engineered for precise radiation detection and measurement, incorporating vital features such as powering and adapting the M4011 Geiger-Müller tube. The TP4056 module enhances its functionality with efficient charging of single-cell lithium-ion or lithium-polymer batteries, integrating thermal regulation, overcurrent protection, and reverse polarity protection for safe operation. In Smart X-ray Geiger Datta Logger, the DS3231 real-time clock module ensures precise time synchronization and event logging, facilitating accurate timestamping of radiation readings. This capability is crucial for monitoring radiation dose accumulation over time and correlating exposure data with specific events or patient movements. Additionally, the ILI9341 TFT LCD controller on the board supports essential functions for display management and high-quality graphics rendering, enhancing usability in radiation monitoring applications.

The user interface consists of two main parts. The first part is dedicated to the dashboard, which displays real-time dose measurements, cumulative dose, and the set of exams for the patient. The second part is dedicated to X-ray dose risk assessment. Before any new examination, the patient can select the new exam type, and the system will check the dose associated with this procedure along with the cumulative dose. If the combined dose exceeds the safety limit, the system will alert the user that the selected procedure is risky and suggest choosing an alternative.

The exposure risk assessment is based on X-ray dose references (Table II) for common procedures [35-36]. This algorithm applies the three fundamental principles of radiation protection: Justification, Optimization and Limitation.

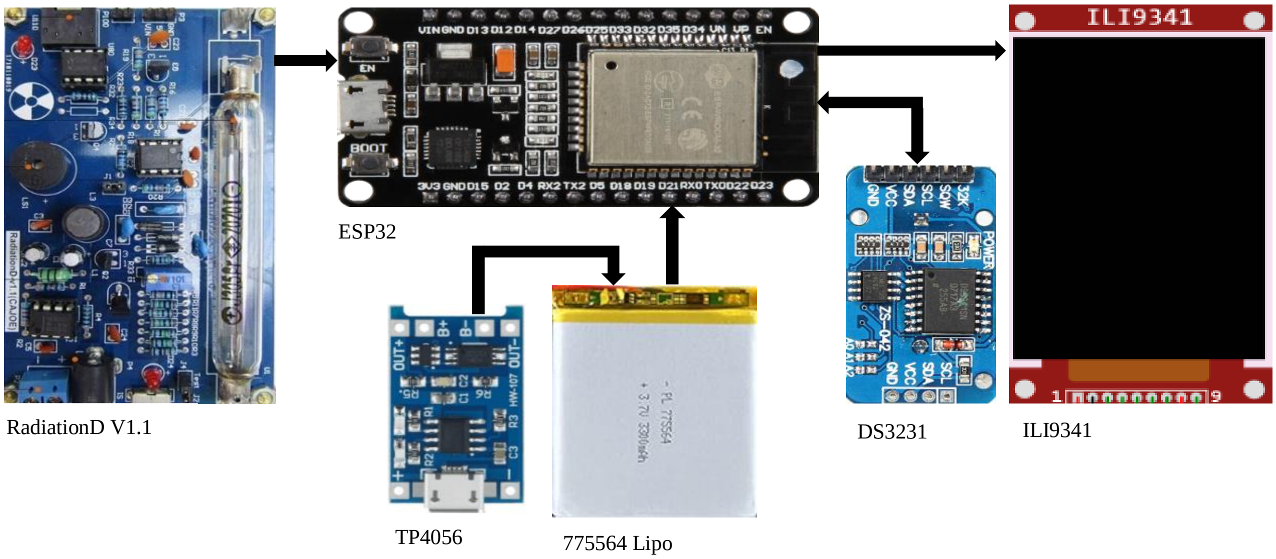

Fig. 3. Smart X-ray Geiger Data Logger diagram.

TABLE II. X-RAY DOSE REFERENCES FOR COMMON PROCEDURES

Procedure	Effective dose mSv
Chest CT	6.1
Abdomen CT	5.3
Brain CT	1.6
Cardiac CT	1.7
Lumbar RS	1.4
Extremity RS	0.1
Chest RS	0.1
Mammography	0.21
Dental	0.25

The Smart X-ray Geiger Data Logger, illustrated in Fig. 4, is engineered to fulfill the objective of measuring, displaying, controlling, and monitoring radiation doses. By embodying these capabilities, it not only upholds stringent principles of radiation safety but also enhances overall radiation protection protocols.

Fig. 5 depicts the flow chart of our solution algorithm. The process begins with powering ON the device and establishing a connection to the database. The user interface then displays real-time dose measurements, cumulative dose, and scheduled exams. The patient selects the type of new exam to be performed, and the device retrieves the dose information associated with the selected exam. The system calculates the total dose by adding the new exam dose to the cumulative dose and evaluates whether this total dose exceeds the safety limit. If it does, a warning message is displayed; if not, the system grants permission for the exam. After the exam, the cumulative dose is updated in the database. The system then checks the updated cumulative dose against the safety limit. If the cumulative dose exceeds the limit, an audible notification is activated and a red LED is turned on. If it does not exceed the limit, the device returns to the dashboard, ready for the next operation, and re-authenticates with the database.

Fig. 4. Smart X-ray Geiger Data Logger for radiation dose measurement and monitoring.

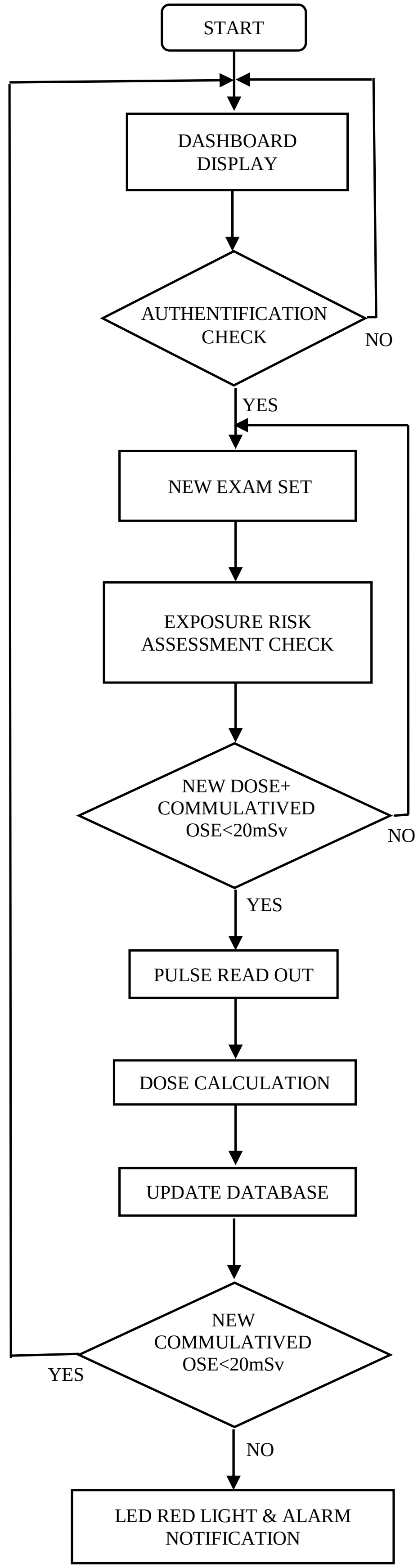

Fig. 5. Algorithm flowchart for radiation dose management system.

III. Results and Discussion

In diagnostic radiology, X-ray dosimetry is essential to optimize imaging procedures and minimize unnecessary radiation exposure to patients. This includes techniques such as computed tomography (CT), fluoroscopy, and conventional radiography. Concerning radiation in therapy, X-ray dosimetry plays a critical role in planning and delivering precise doses of radiation to cancerous tissues while sparing surrounding healthy tissues.

Exposure to prolonged or heightened levels of ionizing radiation elevates the risk of developing cancer, with the specific type and likelihood of cancer contingent upon the organs affected. Robust statistical evidence indicates an increased cancer incidence among populations exposed to substantial radiation doses, as exemplified by survivors of atomic bombings in Hiroshima and Nagasaki [37]. Additionally, elevated radiation doses have the potential to induce heritable genetic mutations. Acute exposure to high doses of radiation can precipitate Acute Radiation Syndrome, characterized by symptoms such as nausea, vomiting, diarrhea, and, in severe cases, damage to organs and tissues, with the severity directly proportional to the dosage.

Radiation protection agencies rely on sophisticated models to project the lifetime risk of cancer resulting from radiation exposure, accounting for variables such as age, gender, and radiation type.

An experiment utilizing the E7239GX Toshiba X-ray tube device was conducted to measure scattered radiation doses across different parameters, as outlined in Table III. This study was undertaken to evaluate the levels of scattered radiation generated under varied operational conditions, a critical factor in assessing radiation safety protocols and refining imaging techniques in medical environments. All measurements were recorded using our Smart X-ray Geiger Data Logger and cross-verified with the BR-6 Geiger counter device, as depicted in Fig. 6. This comprehensive approach ensures accurate data collection and validation, contributing to enhanced understanding and management of radiation exposure in clinical settings.

Fig. 6. Verification of scattered radiation measurements using smart X-ray Geiger Data Logger and BR-6 Geiger counter.

TABLE III. Parameters and Corresponding Scattered Radiation Doses Measured with E7239GX Toshiba X-ray Tube Device

High Voltage (kV)	Filament Current (mA)	Distance from the Source (m)	Dose for Scattered Radiation (uSv)
70	100	1	4.71
70	50	1	4.41
70	20	1	4.36
80	50	1	4.44
90	50	1	4.50
100	50	1	4.53
110	50	1	4.55
70	100	2	1.17
70	50	2	1.10
70	20	2	1.09
80	50	2	1.11
90	50	2	1.12
100	50	2	1.13
110	50	2	1.13

In summary, adjusting high voltage (kV) and filament current (mA) affects the quality and quantity of the X-rays produced, which in turn influence the dose for scattered radiation at different distances from the source. Lowering kV or mA can reduce radiation exposure but may affect image quality, while increasing distance from the source decreases radiation intensity but requires compensation with higher kV or mA settings to maintain diagnostic quality.

However, the amount of scattered radiation dose received can vary significantly depending on several key factors. These include the type of material through which the X-rays scatter, such as bone or soft tissue, and the angle at which scattering occurs. Distance from the radiation source plays a critical role as well, with intensity decreasing according to the inverse square law as distance increases. Effective shielding and room design are crucial in minimizing scattered radiation exposure, as they can absorb or redirect scattered X-rays away from personnel. Patient positioning also influences exposure levels, as different positions can direct scattered radiation towards different areas of the exam room. Additionally, factors related to X-ray equipment, such as tube voltage, current settings, and beam collimation, directly impact the amount of scattered radiation generated.

To manage the power supply, control the Geiger-Müller tube, and acquire measured dose values, we utilized the RadiationD V1.1 board. Fig. 7 illustrates the board's diagram, structured around several key components.

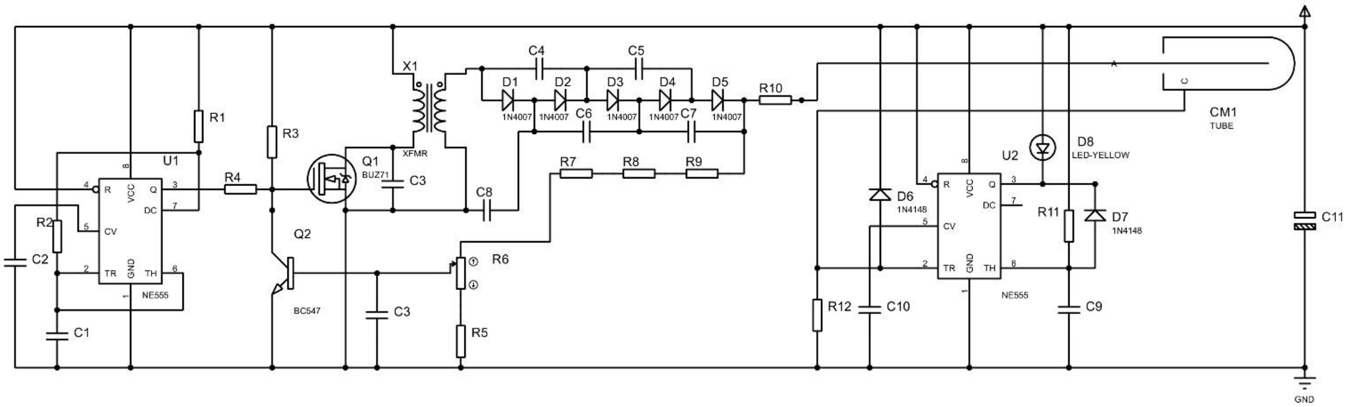

Fig. 7. RadiationD V1.1 board.

The first key component is the Square-Wave Generator Block. This block is tasked with generating a carrier signal that drives the system. The precise timing signals produced by this block ensure synchronization within the system, providing a stable foundation for the subsequent components to function correctly. Next, the High Voltage Power Supply plays a crucial role. This circuit converts the low voltage from the battery to the high voltage required to operate the Geiger-Müller tube, typically in the range of 350-500V. This component is essential for the stable operation of the Geiger-Müller tube, ensuring it receives the necessary high voltage to detect radiation accurately.

The Geiger-Müller Tube itself is a cylindrical tube filled with inert gas that becomes ionized when radiation passes through it. The ionization process generates electrical pulses, which are the primary signal used to detect radiation. This tube is the core of the radiation detection process, as it directly responds to ionizing particles. Capturing these pulses is the job of the Pulse Detection Circuit. This circuit typically consists of a resistor-capacitor (RC) configuration connected to the Geiger-Müller tube. It detects the electrical pulses generated by the tube when radiation is present. This detection circuit is crucial for converting the ionization events within the tube into readable electrical signals.

Finally, the Amplification and Timing Regulation component processes the detected pulses. This part of the board amplifies the pulses to ensure they are strong enough for accurate measurement. Additionally, it regulates the timing to ensure precise dose calculations. Accurate amplification and timing regulation are vital for providing reliable radiation dose values, ensuring that the detected signals are processed correctly.

Fig. 8 represents different amounts of X-ray radiation, depicted as a random signal. This figure illustrates the varying intensities and frequencies of X-ray radiation generated over a period of time, showcasing the fluctuating of radiation levels in the X-ray field.

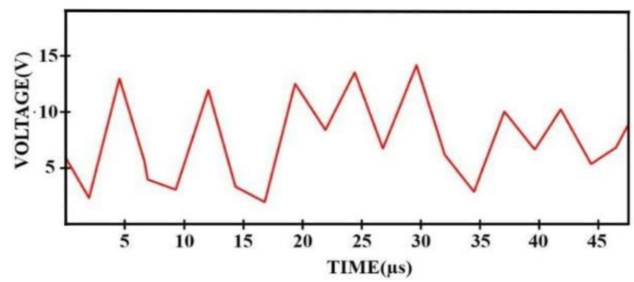

Fig. 8. Different amounts of x-ray radiation represented by a random signal.

Fig. 9 shows the high voltage generated for the Geiger-Müller tube's function. This figure highlights the conversion process from the low voltage power supply to the high voltage necessary for the operation of the Geiger-Müller tube. The stability and consistency of this high voltage are crucial for accurate radiation detection.

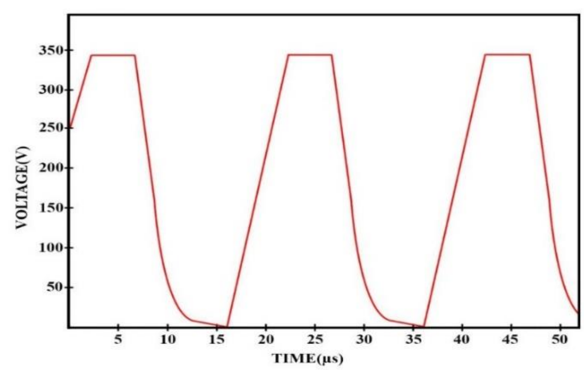

Fig. 9. High voltage generated for Geiger-Müller tube operation.

Fig. 10 represents the pulse detected by the Geiger-Müller tube, which will be transmitted for further processing. This figure demonstrates the output of the pulse detection circuit, showing the discrete electrical pulse generated in response to ionizing radiation passing through the Geiger-Müller tube. These pulses are then amplified and timed correctly for accurate radiation dose measurement and data analysis.

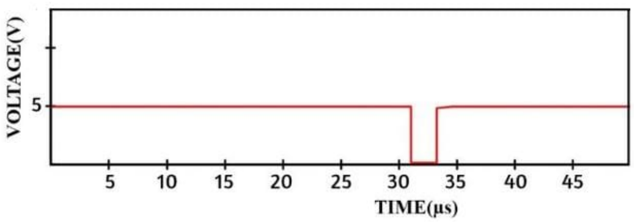

Fig. 10. Pulse detected by the Geiger-Müller tube for processing.

This study illustrates critical components and operational procedures essential for simulating X-ray doses. Among them, the RadiationD V1.1 board is prominently featured, serving as integral hardware for the detection system. These visual representations also depict different levels of X-ray radiation, demonstrating the system's sensitivity and response capabilities. Additionally, the figures demonstrate the generation of high voltage required for Geiger-Müller tube operation, underscoring its pivotal role in detecting radiation. Furthermore, they detail the pulses detected by the Geiger-Müller tube, providing insights into the electrical responses triggered by simulated radiation events. Together, this study offers a comprehensive overview of the experimental setup and operational mechanisms on simulating X-ray doses.

IV. Conclusion

In this study, we introduced the Smart X-ray Geiger Data Logger, a novel device designed for integrated detection, control, and dose evaluation of X-ray radiation. This device addresses the critical need for real-time monitoring and precise measurement of radiation doses in medical imaging and other applications. By leveraging the ionization effect within the Geiger-Müller tube and advanced algorithmic processing, the Smart X-ray Geiger Data Logger offers significant advancements in radiation safety management.

Through our experimental setup and data collection procedures, we demonstrated the device's capability to accurately measure and monitor X-ray doses, providing immediate feedback on both instant and cumulative radiation exposure. The integration of a robust algorithm for exposure risk assessment ensures proactive management of radiation safety, alerting users to potential risks and suggesting alternative procedures when safety limits are approached or exceeded. The Smart X-ray Geiger Data Logger stands poised to contribute significantly to the advancement of radiation safety practices, ensuring enhanced patient care and occupational safety across medical sectors.

Looking forward, the Smart X-ray Geiger Data Logger marks a significant advancement in radiation monitoring, providing healthcare professionals a vital tool for optimizing radiation exposure management.

References

[1] L.B. Youssef, A. Bybi, H. Drissi and E. A. Chater, "Enhancing Radiation Safety in Moroccan Healthcare: A Comprehensive Study on X-Ray Dose Monitoring, Control, and Dosimeter Integration," 2024 4th International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET), FEZ, Morocco, 2024, pp. 1-6, doi: 10.1109/IRASET60544.2024.10548161.

[2] Eaton, D. J., Gonzalez, R., Duck, S., & Keshtgar, M. (2011). Radiation protection for an intra-operative X-ray device. The British journal of radiology, 84(1007), 1034-1039.

[3] Acerbi, F., Altamura, A. R., Di Ruzza, B., Merzi, S., Spinnato, P., & Gola, A. (2023). Characterization of radiation damages on Silicon photomultipliers by X-rays up to 100 kGy. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1045, 167502.

[4] L.B. Youssef, A. Bybi, H. Drissi, and E.A. Chater, "Dose Archiving and Communication System in Moroccan Healthcare: A Unified Approach to X-Ray Dose Management and Analysis," International Journal of Advanced Computer Science and Applications, vol. 15, no. 8, pp. 590-601, 2024.

[5] Fum, W. K. S., Wong, J. H. D., & Tan, L. K. (2021). Monte Carlo-based patient internal dosimetry in fluoroscopy-guided interventional procedures: A review. Physica Medica, 84, 228–240. https://doi.org/10.1016/j.ejmp.2021.03.004.

[6] Yang, S., Zhang, X., Deng, C., Zhang, Y., Xu, F., Guan, L., & Duan, S. (2022). Design of portable multi-function radiation detection system. He Jishu/Nuclear Techniques, 45(11). https://doi.org/10.11889/J.0253-3219.2022.HJS.45.110403.

[7] Johnson, R., & Patel, K. (2022). Novel techniques in X-ray dose detection: A comprehensive review. International Journal of Medical Physics, 38(2), 157-172.

[8] Garcia, M., & Kim, H. (2021). Impact of automated X-ray dose tracking systems on patient safety. Radiation Protection Dosimetry, 50(4), 303-317.

[9] Brown, L**.**, & Nguyen, T. (2020). Enhancing X-ray imaging safety with advanced dosimetry methods. Medical Imaging Journal, 32(1), 45-59.

[10] Thomas, J., & Zhao, L. (2022). Reducing radiation exposure: Innovations in X-ray dose monitoring technologies. Journal of Medical Imaging and Radiation Sciences, *44*(2), 89-103.

[11] Wilson, P., & Martinez, D. (2019). Development of portable X-ray dose detectors for clinical use. *Clinical Radiology Advances, 29*(5), 401-415.

[12] Smith, J., & Lee, A. (2023). Advancements in real-time X-ray dose monitoring for radiological procedures. Journal of Radiological Science and Technology, *45*(3), 211-225.

[13] Robinson, K., & Wang, X. (2021). Real-time X-ray dose management in diagnostic imaging: Challenges and solutions. Journal of Diagnostic Radiology, 39(4), 221-235.

[14] Martinez, R., & Lee, S. (2019). Application of AI in X-ray dose detection and monitoring. *Artificial Intelligence in Medicine, 47*(1), 65-79.

[15] Silva, W. R. F., & Fonseca, J. M. (2023). Development of an X-ray machine, a Geiger detector and a goniometer of low-cost to study X-rays. Revista Brasileira de Ensino de Fisica, 45. https://doi.org/10.1590/1806-9126-RBEF-2023-0073.

[16] International Commission on Radiological Protection (ICRP). (2007). The 2007 Recommendations of the International Commission on Radiological Protection. Annals of the ICRP, 37(2-4), 1-332.

[17] Grasso, S., Varallo, A., Ricciardi, R., Italiano, M. E., Oliviero, C., D'Avino, V., Feoli, C., Ambrosino, F., Pugliese, M., & Clemente, S. (2023). Absorbed dose evaluation of a blood irradiator with alanine, TLD-100 and ionization chamber. Applied Radiation and Isotopes, 200. https://doi.org/10.1016/j.apradiso.2023.110981.

[18] Waqar, M., Ul-Haq, A., Bilal, S., & Masood, M. (2017). Comparison of dosimeter response of TLD-100 and ionization chamber for high energy photon beams at KIRAN Karachi in Pakistan. Egyptian Journal of Radiology and Nuclear Medicine, 48(2), 479–483. https://doi.org/10.1016/j.ejrnm.2017.01.012.

[19] Neves, L. P., Perini, A. P., Fernández-Varea, J. M., Cassola, V. F., Kramer, R., Khoury, H. J., & Caldas, L. V. E. (2014). Dosimetric application of a special pencil ionization chamber in radiotherapy X-ray beams. Radiation Physics and Chemistry, 95, 98–100. https://doi.org/10.1016/j.radphyschem.2012.12.042.

[20] Zhou, M., Hu, L., Huang, L., Zhong, G., Li, K., Hong, B., Xiao, M., & Zhang, R. (2020). Measurement of the radiation dose distribution in EAST hall based on thermoluminescence dosimeter. Fusion Engineering and Design, 160, 111977. https://doi.org/10.1016/J.FUSENGDES.2020.111977.

[21] Del Sol Fernández, S., García-Salcedo, R., Sánchez-Guzmán, D., Ramírez-Rodríguez, G., Gaona, E., de León-Alfaro, M. A., & Rivera-Montalvo, T. (2016). Thermoluminescent dosimeters for low dose X-ray measurements. Applied Radiation and Isotopes, 107, 340–345. https://doi.org/10.1016/J.APRADISO.2015.11.021.

[22] Ghoneam, S. M., Mahmoud, K. R., Diab, H. M., & El-Sersy, A. (2022). Studying the dose level for different X-ray energy conventional radiography by TLD-100. Applied Radiation and Isotopes, 181, 110066. https://doi.org/10.1016/J.APRADISO.2021.110066.

[23] Moradi, F., Mahdiraji, G. A., Rezaee Ebrahim Saraee, K., Khandaker, M. U., Adikan, F. R. M., & Bradley, D. A. (2022). Impact of dosimeter size on energy dependence: An experimental study on glass TLDs. Radiation Physics and Chemistry, 200, 110176. https://doi.org/10.1016/J.RADPHYSCHEM.2022.110176.

[24] Bakkari, M., & Soliman, K. (2018). [P004] Measurment of entrance surface dose during chest X-ray examinations in neonatal intensive care unit using OSL and TLD dosimeters. Physica Medica, 52, 100. https://doi.org/10.1016/J.EJMP.2018.06.337.

[25] Thabit, H. A., Ismail, A. K., Kabir, N. A., al Mutairi, A. M., Bafaqeer, A., Alraddadi, S., Jaji, N. D., Sayyed, M. I., & Al-Ameri, S. M. (2023). Investigation of the thermoluminescence dosimeter characteristics of multilayer ZnO(300 nm)/Ag(50 nm)/ZnO(x) thin films for photonic dosimetry applications. Optical Materials, 137, 113548. https://doi.org/10.1016/J.OPTMAT.2023.113548.

[26] Tang, K., & Zhang, S. (2021). Real-time dosimeter based on LiF:Mg,Cu,P and SiPM. Radiation Measurements, 145, 106607. https://doi.org/10.1016/J.RADMEAS.2021.106607.

[27] Posar, J. A., Davis, J., Brace, O., Sellin, P., Griffith, M. J., Dhez, O., Wilkinson, D., Lerch, M. L. F., Rosenfeld, A., & Petasecca, M. (2020). Characterization of a plastic dosimeter based on organic semiconductor photodiodes and scintillator. Physics and Imaging in Radiation Oncology, 14, 48–52. https://doi.org/10.1016/J.PHRO.2020.05.007.

[28] Pejović, M. M., & Pejović, S. M. (2023). P-channel MOSFET as ionizing radiation detector. Applied Radiation and Isotopes, 196. https://doi.org/10.1016/j.apradiso.2023.110730.

[29] Matsumoto, T., Yamaguchi, K., Yanagisawa, R., Kubodera, K., Arai, Y., Makino, T., Ohshima, T., Sakai, M., Matsumura, A., & Kada, W. (2023). Development of a SiC semiconductor-based dosimeter for evaluating clinical dose distribution in carbon ion cancer therapy fields. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 542, 151–157. https://doi.org/10.1016/j.nimb.2023.06.013.

[30] Jung, H., Lee, K. J., Kim, J. L., & Lee, S. Y. (2004). Development of a personal dosimeter badge system using sintered LiF:Mg,Cu,Na,Si TL detectors for photon fields. Radiation Measurements, 38(1), 71–80. https://doi.org/10.1016/j.radmeas.2003.08.006.

[31] Yamadera, A., Kim, E., Miyata, T., & Nakamura, T. (1995). Development of high sensitivity X-and λ-ray personal dosimeter using photostimulated luminescent detector. Applied Radiation and Isotopes, 46(6–7), 467–468. https://doi.org/10.1016/0969-8043(95)00053-4.

[32] Alnawaf, H., Butson, M. J., Yu, P. K. N., & Cheung, T. (2011). SIRAD – Personal radiation detectors. Radiation Measurements, 46(12), 1826–1828. https://doi.org/10.1016/J.RADMEAS.2011.07.027.

[33] Guo, C. Y., Lin, T. L., & Hsieh, T. L. (2022). A Solar-Rechargeable Radiation Dosimeter Design for Radiation Hazard Zone Located with LoRa Network. Quantum Beam Sci. 2022, 6, 27.

[34] Babiuch, M., Foltýnek, P., & Smutný, P. (2019, May). Using the ESP32 microcontroller for data processing. In 2019 20th International Carpathian Control Conference (ICCC) (pp. 1-6). IEEE.

[35] Osman, H., Ahmed, A. M., Musa, A., Medani, A., Abouraida, R. A., Alelyani, M., ... & Awadallah, B. A. (2024). Radiation dose assessment: Establishment of local diagnostic reference levels for selected radiography examinations across three prominent hospitals in Sudan. Radiation Physics and Chemistry, 217, 111482.

[36] M. Alkhorayef, A. Sulieman, Khalid Alzahrani, Mohamed Abuzaid, Othman I. Alomair, M. Almuwannis, Salem Alghamdi, Nissren Tamam, David A. Bradley, Radiation risk for patients undergoing cardiac computed tomography examinations, Applied Radiation and Isotopes, Volume 168, 2021, 109520, ISSN 0969-8043, https://doi.org/10.1016/j.apradiso.2020.109520.

[37] Chun, C. K. S. (2008). *Japan 1945:* From Operation Downfall to Hiroshima and Nagasaki. Osprey Publishing.