MEDIDA DA TAXA DE DOSE DE RADIAÇÃO PARA PROGRAMAS DE PROTEÇÃO NO AMBIENTE DE TRABALHO PARA OS TRABALHADORES DE SAÚDE: UM ESTUDO EXPERIMENTAL

RADIATION DOSE RATE MEASUREMENT FOR PROTECTION PROGRAMS IN THE WORK ENVIRONMENT FOR THE HEALTH WORKERS: AN EXPERIMENTAL STUDY

PENGUKURAN LAJU DOSIS RADIASI UNTUK PROGRAM PROTEKSI RADIASI DI LINGKUNGAN KERJA BAGI PEKERJA KESEHATAN: KAJIAN EKSPERIMENTAL

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RESUMO

A radiação é a energia emitida pelos elétrons na forma de partículas ou fótons (ondas), sendo classificada em não ionizada e ionizada. A radiação ionizante demonstra a capacidade de desintegrar a matéria ao longo de seu caminho e tem se mostrado benéfica na medicina. A exposição a essa energia tende a instigar efeitos adversos na saúde humana e na hereditariedade (genética). No entanto, a radiação não é medida diretamente, mas requer detector nuclear para servir como um dispositivo de monitoramento. A consciência dos trabalhadores de radiação sobre os níveis de radiação ionizante no ambiente de trabalho é um dos fatores mais importantes na prevenção dos efeitos negativos da radioatividade. Isso é possivelmente identificado por meio de vários tipos de detectores. O objetivo deste experimento foi fornecer uma visão geral sobre a medição da taxa de dose de radiação em duas condições. O primeiro é o caso de contaminação no ambiente de trabalho e o segundo envolve o uso de detector para determinar apenas a taxa de dose de uma única fonte, por exemplo, radiação gama. Portanto, a taxa de dose de radiação foi avaliada maximizando o uso de detectores equipados com uma GUI como um medidor de pesquisa de contaminação. A maior taxa (261,42 $\mu\text{Sv} / \text{h}$) foi observada na distância de 5 mm, enquanto a menor (69,21 $\mu\text{Sv} / \text{h}$) foi registrada a 50 mm. Além disso, uma taxa de dose de 5,4 $\mu\text{Sv} / \text{h}$ e 1,32 $\mu\text{Sv} / \text{h}$ foi obtida a uma distância de 5 mm e 50 mm da fonte de radiação, respectivamente, seguindo a operação como medidor de gama. Este resultado mostra a presença de forte linearidade entre as duas medições e é estimado para determinar com precisão o nível de contaminação dos elementos radioativos, juntamente com a taxa de dosagem dos elementos emissores de radiação gama.

Palavras-Chave: *Detector de radiação, taxa de dose de radiação, proteção contra radiação e radiação ionizante*

ABSTRACT

Radiation is the energy emitted from electrons in particles or photons (waves) and is classified into non-ionized and ionized. Ionizing radiation demonstrates the ability to disintegrate matter along its path and has proven beneficial in medicine. Exposure to this energy tends to instigate adverse effects on human health and heredity (genetics). However, the radiation is not directly measured but requires a nuclear detector to serve as a monitoring device. Radiation workers' awareness of ionizing radiation levels in the work environment is one of the most important factors in preventing the negative effects of radioactivity. This is possibly identified using various types of detectors. This experiment aimed to provide an overview of radiation dose rate measurement under two conditions. First is the event of contamination in the work environment. The second involves using a detector to solely determine the dose rate from a single source, e.g., gamma radiation. Therefore, the radiation dose rate was evaluated by maximizing the use of detectors with a GUI as a survey meter for contamination. The highest rate (261.42 $\mu\text{Sv} / \text{h}$) was observed at a distance of 5 mm, while the least (69.21 $\mu\text{Sv} / \text{h}$) was recorded at 50 mm. Also, a dose rate of 5.4 $\mu\text{Sv} / \text{h}$ and 1.32 $\mu\text{Sv} / \text{h}$ was obtained at a 5 mm and 50 mm distance from the radiation

source, respectively, following the operation as a gamma survey meter. This result shows strong linearity between both measurements and is estimated to accurately determine the contamination level of radioactive elements, alongside the doses rate of the gamma radiation emitting elements.

Keywords: *Radiation Detector, Radiation Dose Rate, Radiation Protection, and Ionizing Radiation*

ABSTRAK

Radiasi adalah pancaran energi yang berasal dari partikel atau foton. Berdasarkan kemampuan mengionkan materi, radiasi dapat dikelompokkan menjadi radiasi non-pengion dan radiasi pengion. Radiasi pengion adalah radiasi yang dapat mengionkan materi yang dilaluinya. Radiasi pengion telah terbukti bermanfaat dalam bidang kedokteran. Namun, paparan radiasi pengion potensial dapat menyebabkan efek negatif bagi kesehatan dan keturunan (genetik). Radiasi pengion juga tidak dapat diamati secara langsung sehingga diperlukan suatu detektor nuklir sebagai alat pemantau radiasi. Kesadaran akan tingkat radiasi pengion di sekitar lingkungan pekerja radiasi adalah salah satu faktor terpenting untuk mencegah dampak negatif penggunaan radiasi pengion. Hal ini dapat diketahui melalui penggunaan detektor radiasi dari berbagai jenis. Artikel ini melaporkan tentang teknik pengujian laju dosis radiasi dengan memaksimalkan penggunaan detektor radasi yang telah dilengkapi dengan GUI. Penelitian ini dilakukan dengan pendekatan eksperimental guna untuk memberikan gambaran proses pengukuran laju dosis radiasi ketika terjadi kontaminasi pada daerah kerja dan ketika detektor difungsikan hanya untuk mengetahui laju dosis radiasi yang berasal dari sumber tunggal yaitu radiasi gamma. Pada saat detektor difungsikan sebagai survey meter kontaminasi, didapatkan laju dosis radiasi tertinggi pada jarak 5 mm yaitu 261.42 $\mu\text{Sv/h}$ dan terendah pada jarak 50 mm sebesar 69.21 $\mu\text{Sv/h}$. Pada saat detektor sebagai survey meter gamma didapatkan laju dosis radiasi 5.4 $\mu\text{Sv/h}$ pada posisi 5 mm dan 1.32 $\mu\text{Sv/jam}$ pada posisi detektor 50 mm dari sumber radiasi. Hasil menunjukkan linearitas antara kedua pengukuran sangat kuat. Teknik pengukuran ini akurat untuk menentukan kontaminasi dari unsur radioaktif dan menentukan laju dosis radiasi dari unsur yang memancarkan radiasi gamma.

Kata kunci: *Detektor Radiasi, Laju Dosis Radiasi, Proteksi Radiasi, dan Radiasi Pengion*

1. INTRODUCTION:

Radiation is generally defined as the radiant energy generated from particles or photons. The source materials are classified by Stabin (2007) into (1) ionizing radiation, capable of ionizing the matter in its path, including photons, with wavelengths <1 nm or equivalent to 12 eV energy, as well as alpha, neutron, and beta (Ryan *et al.*, 2012). (2) the non-ionizing group comprises photons with wavelengths > 1 nm, as observed with radio waves and sunlight (Rosenberg, 2008). Based on this analysis, all the radiation terms used subsequently in this article refer to the ionizing type.

Radiation confers positive effects, as shown in various fields, including medical practice, radiodiagnostics, radiotherapy, and nuclear medicine. Radiation is applied in diagnostic radiology to detect potential diseases, bone abnormalities, and cancer (Krhovska *et al.*, 2019). The energy is also employed in radiotherapy as a treatment technique, particularly in eliminating cancer cells in organs or tissues. This is achieved by maximizing radiation dose in the cancerous tissue and minimizing the healthy peer (Benedict *et al.*, 2010). Meanwhile, radioactivity is fast gaining broader recognition in nuclear medicine and is characterized by radiopharmaceuticals known as radiopharmaceuticals for diagnostic and

radiotherapy purposes. (Missailidis *et al.*, 2007).

Furthermore, CT (computed tomography) scans are among significant utility instances applied to detect abnormalities or diseases (Kusminarto, 2015), (Fitousi, 2017). Also, cobalt-60 machines and medical linear accelerators are widely used for radiotherapy from external sources (Healy *et al.*, 2017). However, radiopharmaceuticals have been widely reported as a means for diagnosing bone metastasis (Hsia *et al.*, 2002), (Saeed *et al.*, 2017), and cancer therapy in nuclear medicine (Luster *et al.*, 2008). Recent studies have shown radiopharmaceuticals' development as a carrier of pain medicines or cancer cells' treatment in targeted organs (Kazakov *et al.*, 2020).

The application of ionizing radiation has witnessed a drastic upsurge due to rapid development in medical technology. However, the risk to health, both in patients and medical professionals, has also increased due to steady exposure to these radiations as modern evolution continues. Furthermore, ionizing radiation has become a major energy source from non-natural sources (Teles *et al.*, 2020). The adverse effects of radiation are grouped according to latency into direct (deterministic) and stochastic (delayed) (Santos, 2020). Remarkably, the deterministic impact is reported at doses more significant than

a certain threshold (Tubiana, 1998), and is generally observed immediately after exposure. Meanwhile, stochastic effects possibly occur in any predisposed individual (Richardson, 2015) and are characterized by (1) no threshold dose, (2) effect probability rises at higher levels, and (3) ascertained effect concerning the exposure (Radford, 1980). Furthermore, cancer is one of the diseases included in this category (Nambiar, 2011), (Mohan *et al.*, 2003), (Paunesku *et al.*, 2017), (Averbeck *et al.*, 2007).

The five human senses cannot directly detect nuclear radiation due to the absence of any biological sensors (Fardela *et al.*, 2019). Therefore, the risks or unwanted impacts are reduced by using a device or dosimeter to determine the presence of radiation. This instrumentation system is applied to measure and evaluate exposure values, kerma, and absorbed or equivalent doses associated with ionizing radiation, both directly and indirectly (Podgorsak, 2005).

The radiation dosimeters are divided into two groups, in the aspect of reading, including (1) the passive types, comprising measurement results, which is difficult to read directly. Hence, there is a need for initial special processing (Knoll, 2007), including film badge and thermoluminescent dosimeter (TLD) (Magalotti *et al.*, 2014). Medical personnel within the area of interventional radiology (IVR) are at risk of exposure to high doses of scattered radiation emitted from the patient (Fujibuchi *et al.*, 2019). For instance, the cardiologist site doses are spread out in the range from 1-14 mSv/hour during fluoroscopy. Workers in planned exposure situations are advised an equivalent dose limit of 20 mSv / year for eye lenses (Miller, 2018), averaged over five years with one-year exposure restricted to 50 mSv, based on ICPR recommendation (Fujibuchi, *et al.*, 2019) (Revised Law on the prevention of radiation hazards due to radioisotopes). This condition tends to increase the cataract risk for IVR personnel known to exceed the annual dose limit. Therefore, the management of additional occupational exposure is necessary. Medical personnel must always wear protective clothing (Apron) and use a passive type of personal dosimeters, including glass or quixel badge. This kind of device is shared among clinical practitioners. However, the inability to directly measure the radiation dose presents a disadvantage (Fujibuchi *et al.*, 2019).

The active dosimeters (2) generate results to be read directly, encompassing surveillance meters, pocket dosimeters, or the recently known

personal electronic dosimeters (EPD) or Active Person Dosimeters (APD) (Tsoulfanidis, 2010). Besides, the active device instantly displays the radiation dose, and exposure received compared to passive dosimeters (Benevides *et al.*, 2014). This provides a picture and a signal for exceeding the threshold (Fujibuchi *et al.* (2019).

Research on radiation dose rate measurements at facilities with nuclear techniques has been widely conducted. Mustofa *et al.*, 2019 reported on the desirable features of commercial EPD to be applied in radiation protection. Therefore several tests were performed, including reproducibility, dose linearity, dose rate, and angular dependence using a Cs-137 radiation source. Moreover, EPD has been used to monitor the radiation dose rate for workers' radiation protection (Taleb, 2013), (Fardela, 2018). Furthermore, Suliman *et al.* (2020) reported on the application to scrutinize the level received by some staff, doctors, and workers in the field of nuclear medicine. Therefore, the lack of radiation control programs and the use of occupational exposure control devices were of significant concern (Suliman, 2019).

One of the most important factors to be considered by workers in this field is the awareness of radiation level; therefore, various types of detectors are being adopted in the identification process. However, a basic understanding of the respective action mechanism is assumed to help make the best selection and maximize operational benefits. Currently, an active radiation detector shows the results of real-time radiation dose rate measurements (Donowsky, 2013). This helps the medical workers to maximize protection in an exposed work environment. However, not every employee is acquainted with detailed procedures despite being relatively expensive.

Therefore, this study aimed to provide an overview of the radiation dose rate measurement in a contaminated work environment and the use of a detector to exclusively determine the radiation dose from a single source (gamma radiation). The novelty of this study lies in the methodology and communication systems applied in the retrieval process using an active dosimeter, which is directly connected to a centralized real-time data acquisition system.

2. MATERIALS AND METHODS:

This article reports the radiation dose rate testing technique, using a radiation dosimeter equipped with a GUI (Graphical User Interface).

Furthermore, the unit was serially connected to a computer, and the respective placements and utilization techniques were substantially considered. These placements influence the measure of radiation dose rate. However, incorrect application hinders the possibility of describing the investigated condition, thus leading to errors in understanding the monitoring data results obtained from the work area. Therefore, this study focuses on measuring the radiation dose rate from various emission sources, including alpha particles, beta, and gamma radiation. Besides, this approach is expected to serve as a guide towards the rate determination for other elements. The study outcome is anticipated to be the basis for maximizing the use of radiation detector, and also to develop protection in ionized environments. The study was conducted at the Atomic and Nuclear Physics Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada.

2.1. Materials and Tools

The material used included radioactive Cesium 137 (Cs-137) with activity (72483.97 ± 3%) Bq, characterized by an energy peak of 661 keV (Kefalidis *et al.*, 2017), and emits beta as well as gamma radiation. The radiation source activity (Cs-137) was calculated using equation 1 (Mann, 2012).

$$\frac{A_t}{A_0} = \left(\frac{1}{2}\right)^{\frac{t}{T}} \quad (1)$$

Where A_t is the activity of the radioactive elements over t time in Bq units. A_0 is the initial elemental activity in Bq units, T is the half-life in years, and t is the present time in years. Using available data i.e., $A_0 = 80426$ Bq, $T = 30,05$ years, and $t = 4,5$ years, A_t is determined by equation 2:

$$\begin{aligned} \frac{A_t}{80426 \text{ Bq}} &= \left(\frac{1}{2}\right)^{\frac{4,5}{30,05}} \\ A_t &= 72483,97 \text{ Bq} \end{aligned} \quad (2)$$

Therefore, the activity of the element radioactive at the time of data collection is evaluated at (72483.97 ± 3%) Bq.

The following tools were used: (a) Commercial radiation dosimeter, termed "Radiation Alert Ranger Radiation Detector". This is assumed sensitive to alpha, beta, and gamma

radiation, and is possibly connected serially to the computer with the help of a USB cable. The calibration factor is specified at 0.94, which is multiplied by the value of the measurement results. This value observes an operating range, including (0.001-100) mR / hr, (0-350000) cpm, (0.01-1000) μSv / hr, (0-5000) cps, and a total counts of 1 - 9999000. (b) The PC used to install the GUI program was provided by the "Radiation Alert Detector" and can save and display the radiation exposure rate monitoring process. (c) Lead (Pb) is used as a shield from radiation sources during the data collection process. (d) The detector is equipped with a real to vary the distance from the radiation source. The software used in this study was accessed at the following link <https://seintl.com/radiation-detectors/radiation-alert-software/>.

2.2. Method

Radiation exposure rate data was captured using a "radiation alert detector." This involved placing Cs-137 in a box already blocked by lead to prevent radioactive contamination around the study site. The background radiation rate was first determined before the radioactive element is removed from storage. Therefore, the measurements obtained were reduced by background radiation and multiplied by the detector correction factor.

A total of two data collection processes were performed, including (1) Determination of exposure rate, originating from the gamma energy emitted from Cs-137, as follow:

- This requires setting the detector rear window in a closed condition to allow for specific recognition and measurement.
- Figure 1 shows the test box was designed using available lead (Pb) at the Atomic and Core Physics Laboratory.
- The temperature and background radiation in the work environment is determined and recorded.
- The radioactive element (Cs-137) is situated in a box designed and coated with lead (Pb).
- The detector rail is placed in the box, where the radiation detector is placed at the detector rail position, as shown in Figure 1.
- The distance between the radiation detector and the source is specified at 10 mm.

- g. A set of detectors employed has been confirmed fit to communicate serially with the computer.
- h. Furthermore, radiation exposure is measured around the work environment by the Atomic and Core Laboratory Radiation Protection Officers to prevent contamination from the system (Box).
- i. On the computer connected to the detector, the data storage time is determined every 5 seconds.
- j. Measurements were performed repeatedly for each distance between dosimeters and radiation sources, termed 5 mm, 10 mm, 15 mm, up to 50 mm.
- k. The data obtained is in the form of radiation dose in units of $\mu\text{Sv} / \text{h}$.
- l. At the end of the process, click stop on the GUI screen available on the PC (computer).

And (2) Determination of exposure from beta particles and gamma radiation. This involved opening the detector rear window lid to measure all emission types (beta, gamma, and alpha) from Cs-137. Steps (a) to (i) were repeated by varying the distance of the detector to the radiation source by 5, 10 to 50 mm. Furthermore, the radiation exposure rate results were sent to the computer through serial communications, using a USB cable, subsequently displayed in graphics, TXT, and saved in a memory device.

2.3. Analysis

The experimental results are in the form of research data. This data was then processed using the origin data processing program to determine the standard deviation and graph plot. The linearity between the measurement results of the contamination detector dose rate and the gamma detector were also evaluated. To ascertain the linearity, a graph of the relationship between the contamination detector dose rate ($\mu\text{Sv} / \text{hour}$) (x_i) and the gamma detector output (y_i) was plotted. Furthermore, the linear function involves the standard deviation of the repeated measurement results by equation 3.

$$y(x) = a + bx \quad (3)$$

The least-squares fitting procedure minimizes X^2 with the associated coefficient, as shown in equation (4) (Bevington, 1969).

Chi-square (χ^2) (equation 4):

$$\chi^2 = \sum \left[\frac{1}{\sigma_i^2} (y_i - a - bx_i)^2 \right] \quad (4)$$

The a is the intercept to the y -axis, which is the offset value, as shown in equation (5), or the output signal when the input signal is zero. Meanwhile, b represents the line slope, representing the sensitivity of the detector, as shown in equation (6).

$$a = \frac{1}{\Delta} \left(\sum \frac{x_i^2}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2} \right) \quad (5)$$

$$b = \frac{1}{\Delta} \left(\sum \frac{1}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2} \right) \quad (6)$$

where Δ was calculated using equation (7).

$$\Delta = \sum \frac{1}{\sigma_i^2} \sum \frac{x_i^2}{\sigma_i^2} - \left(\sum \frac{x_i}{\sigma_i^2} \right)^2 \quad (7)$$

The estimated variance s^2 was showed by equation (8).

$$\sigma^2 \cong s^2 = \frac{1}{N-2} \sum (y_i - a - bx_i)^2 \quad (8)$$

$\sigma^2 \cong x_i$ for radiation dose rate data (Bevington, 1969), the uncertainty values of the coefficients a and b are shown in equations (9) and (10).

$$\sigma_a^2 \cong \frac{1}{\Delta} \sum \frac{x_i^2}{\sigma_i^2} \quad (9)$$

$$\sigma_b^2 \cong \frac{1}{\Delta} \sum \frac{1}{\sigma_i^2} \quad (10)$$

where σ_a^2 is uncertainty values of a and σ_b^2 is uncertainty values of b .

3. RESULTS AND DISCUSSION:

The radiation detector used in this research was equipped with a GUI to monitor the average dose rate. This was performed in a distance of 1 meter, or as long as the USB available. Therefore, the data obtained with this interface is automatically saved on a computer to reduce potential errors in reading the average dose rate values. Also, it was possible to reduce the observer's acceptance of the determinations at a specific time by 98%. This required the manual process of recording results, for output received to

be relatively large. The GUI to be equipped with several choices on units, capable of being changed according to the user's preferences. These include $\mu\text{Sv} / \text{h}$, CPM, or others.

Furthermore, the timing of data retrieval is known as a whole, and most importantly, it was possible to save the measurement results on a computer for evaluation. Figure 2 shows a variation in the data obtained, according to the distances for monitoring Cs-137 radiation contamination. Furthermore, the intensity was determined to be identical with the dose rate, which is inversely influenced by the square of the distance between the point and radiation source (Kang *et al.*, 2016), as in equation 11.

$$\dot{D}_1 : \dot{D}_2 = \frac{1}{(R_1)^2} : \frac{1}{(R_2)^2} \quad (11)$$

where $\dot{D}$ is the radiation dose rate in $\mu\text{Sv}/\text{h}$, and R is the distance in meters. Figure 2 shows a decline in the radiation dose rate with increasing distance between the detector and source. Also, the intensity produced radiates in all directions, thus facilitating the rate determination at a point.

Figure 2 shows the capture of all radiation types from element Cs-137, including beta and gamma. This prompted a greater rate of $261.42 \mu\text{Sv} / \text{h}$ at the 5 mm distance, while $69.21 \mu\text{Sv} / \text{h}$ was the least at 50 mm. The decay results of Cs-137 evidence the detector function as a survey meter for contamination. This was perceived by the entry of Beta particles into the detector window, thus prompting more ionization power than gamma radiation. Furthermore, the detector was used to measure the dose rate of gamma radiation emitted by Cs-137 by closing the collimator window on the device's back.

The results (Figure 3) indicate a simultaneous decline in the resulting radiation dose rate at other positions. The value recorded in Figure 3 was smaller than Figure 2, because only gamma radiation was increased, while the beta and alpha particles were not measurable. Therefore, a reduction in the ionization power was observed, marked by a lower radiation dose rate, ranging from $1,32 \mu\text{Sv} / \text{h}$ at the detector position 50 mm to $5.4 \mu\text{Sv} / \text{h}$, at 5 mm from the radiation source. Furthermore, precise measurements were ascertained by plotting a linear relationship between the contamination dose rates and the gamma detector, as presented in Figure 4.

Therefore, the equation of the line obtained was $y = -0.081 + 0.021 * X$, with a solid correlation value of $R^2 = 0.99$. The slope and

intercept were determined as 0.021 and -0.081, respectively. Figure 4 shows accuracy in this measurement technique, following the application in deciding radioactive element contamination and doses rate responsible for gamma radiation emission. Besides, maximizing the detector function helps in improving protection. This result is expected to reduce the negative effects caused by ionizing radiations on workers. Also, it is necessary for handlers to understand the working principle of the operating detector to precisely and accurately determine the radiation dose rate.

4. CONCLUSIONS:

An experimental study of ionizing radiation dose rate measurement techniques designed to improve field workers' protection was completed. This assessment technique significantly influenced the outcome. Furthermore, application as a contamination detector showed a ratio value 50 times greater than the records obtained from measuring the gamma radiation dose rate. The method represents the accuracy of radiation dose rate measurement, both in detector as a contamination survey meter and as a gamma radiation sensor. Also, an active radiation dosimeter provided great assistance to radiation workers to directly determine radioactive elements' contamination. Moreover, direct, precise, and documented picture of the dose rate using a computer device is possible to achieve.

The following potential developments for this research area are proposed: 1) assessing the use of wireless systems with detectors from increased acquisition systems, during the collection of data related to radiation exposure rates, 2) It is necessary to obtain measurements from sources often utilized in the field of nuclear medicine, including Tc-99m, I-131, and others. This aims to maximize the use of radiation dosimeters, and ensure protection in nuclear medicine.

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6. REFERENCES:

1. Averbeck, D., Salomaa, S., Bouffler, S., Ottolenghi, A., Smyth, V., and Sabatier, L. (2018). Progress in low dose health risk research: Novel effects and new concepts in low dose radiobiology. *Mutation Research/Reviews in Mutation Research*, 776, 46-69.
2. Benedict, S. H., Yenice, K. M., Followill, D., Galvin, J. M., Hinson, W., Kavanagh, B., and Purdie, T. (2010). Stereotactic body radiation therapy: the report of AAPM Task Group 101. *Medical physics*, 37(8), 4078-4101.
3. Benevides, L. A., Piper, R. K., and Romanyukha, A. (2014). A performance comparison of Thermo Fisher EPD-MK2 and TLD (LiF: Mg, Cu, P) as part of accreditation proficiency testing. *Radiation measurements*, 71, 183-186.
4. Bevington, P., 1969, *Data Reduction and Error Analysis for The Physical Sciences*, McGraw-Hill Book Company, United States of America.
5. Donowsky, M. (2013). *U.S. Patent Application No. 13/488,850*.
6. Fardela, R., and Ashari, A. (2018, October). Study of Wireless Sensor Network Application for Dosimeter Personal Real Time. In *2018 International Conference on Orange Technologies (ICOT)* (pp. 1-4). IEEE.
7. Fardela, R., Suparta, G. B., Ashari, A., and Triyana, K. (2019). Multi Sensor Data Acquisition System Design for Monitoring the Radiation Dose Based on Wireless Sensor Network. *International Journal of Engineering Research and Technology*. Vol.12, Number 6, pp. 848-853.
8. Fitousi, N. (2017). Patient dose monitoring systems: a new way of managing patient dose and quality in the radiology department. *Physica Medica*, 44, 212-221.
9. Fujibuchi, T., Inoue, A., Ishigaki, Y., and Matsumoto, Y. (2019). Development of a wireless multisensor active personal dosimeter-tablet system (The 9th International Symposium on Radiation Safety and Detection Technology (ISORD-9)). *Progress in nuclear science and technology*, 6, 73-76.
10. Healy, B. J., van der Merwe, D., Christaki, K. E., and Meghzifene, A. (2017). Cobalt-60 machines and medical linear accelerators: competing technologies for external beam radiotherapy. *Clinical Oncology*, 29(2), 110-115.
11. Hsia, T. C., Shen, Y. Y., Yen, R. F., Kao, C. H., and Changlai, S. P. (2002). Comparing whole body 18F-2-deoxyglucose positron emission tomography and technetium-99m methylene diophosphate bone scan to detect bone metastases in patients with non-small cell lung cancer. *Neoplasma*, 49(4), 267-271.
12. Kang, H. G., Song, J. J., Lee, K., Nam, K. C., Hong, S. J., dan Kim, H. C. (2016). An investigation of medical radiation detection using CMOS image sensors in smartphones. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 823, 126-134.
13. Kefalidis, E., Kandarakis, I., and David, S. (2017). Performance characteristics of a personal gamma spectrometer based on a SiPM array for radiation monitoring applications. *JPhCS*, 931(1), 012019
14. Kazakov, A. G., Garashchenko, B. L., Yakovlev, R. Y., Vinokurov, S. E., Kalmykov, S. N., and Myasoedov, B. F. (2020). An experimental study of sorption/desorption of selected radionuclides on carbon nanomaterials: a quest for possible applications in future nuclear medicine. *Diamond and Related Materials*, 104, 107752.
15. Knoll, G. F. (2010). *Radiation detection and measurement*. John Wiley and Sons.

16. Krhovska, P., Minarik, J., Pika, T., Bacovsky, J., and Proskova, J. (2019). Comparison of Radiodiagnostic Methods (Conventional Radiography, Low-Dose Computed Tomography and Magnetic Resonance Imaging) With Selected Markers of Bone Metabolism and Bone Marrow Microenvironment. *Clinical Lymphoma, Myeloma and Leukemia*, 19 (10), e191.
17. Kusminarto, and Fadela, R. (2015). An X-Ray Detector Using a Fluorescent Material ZnS:Ag Attached on a Phototransistor in Darlington Configuration. *Applied Mechanics and Materials*, 771, 21–24. <https://doi.org/10.4028/www.scientific.net/amm.771.21>
18. Luster, M., Clarke, S. E., Dietlein, M., Lassmann, M., Lind, P., Oyen, W. J. G., and Bombardieri, E. (2008). Guidelines for radioiodine therapy of differentiated thyroid cancer. *European journal of nuclear medicine and molecular imaging*, 35(10), 1941.
19. Magalotti, D., Bissi, L., Conti, E., Paolucci, M., Placidi, P., Scorzoni, A., and Servoli, L. (2014). Performance of CMOS imager as sensing element for a real-time active pixel dosimeter for interventional radiology procedures. *Journal of Instrumentation*, 9(01), C01036.
20. Mann, W. B., Rytz, A., and Spornol, A. (Eds.). (2012). *Radioactivity measurements: principles and practice*. Elsevier.
21. Miller, D. L. (2018). Make radiation protection a habit. *Techniques in vascular and interventional radiology*, 21(1), 37-42.
22. Missailidis, S., and Perkins, A. (2007). Update: aptamers as novel radiopharmaceuticals: their applications and future prospects in diagnosis and therapy. *Cancer biotherapy and radiopharmaceuticals*, 22(4), 453-468.
23. Mohan, A. K., Hauptmann, M., Freedman, D. M., Ron, E., Matanoski, G. M., Lubin, J. H., ... and Linet, M. S. (2003). Cancer and other causes of mortality among radiologic technologists in the United States. *International journal of cancer*, 103(2), 259-267.
24. Musto, E., Assenmacher, F., Hofstetter-Boillat, B., Mayer, S., and Yukihara, E. G. (2019). Use of the D-Shuttle dosimeter for radiation protection of members of the public: Characterization and feasibility study. *Radiation Measurements*, 129, 106208.
25. Nambiar, D., Rajamani, P., and Singh, R. P. (2011). Effects of phytochemicals on ionization radiation-mediated carcinogenesis and cancer therapy. *Mutation Research/Reviews in Mutation Research*, 728(3), 139-157.
26. Paunesku, T., Haley, B., Brooks, A., and Woloschak, G. E. (2017). Biological basis of radiation protection needs rejuvenation. *International Journal of Radiation Biology*, 93(10), 1056-1063.
27. Podgorsak, E. B. (2005). Radiation oncology physics. Vienna: *International Atomic Energy Agency*, 123-271.
28. Radford, E. P. (1980). Human health effects of low doses of ionizing radiation: the BEIR III controversy. *Radiation Research*, 84(3), 369-394.
29. Richardson, D. B., Cardis, E., Daniels, R. D., Gillies, M., O'Hagan, J. A., Hamra, G. B. and Schubauer-Berigan, M. K. (2015). Risk of cancer from occupational exposure to ionizing radiation: retrospective cohort study of workers in France, the United Kingdom, and the United States (INWORKS). *Bmj*, 351.
30. Rosenberg, I. (2008). Radiation oncology physics: a handbook for teachers and students. *British journal of cancer*, 98(5), 1020.
31. Ryan, J. L. (2012). Ionizing radiation: the good, the bad, and the ugly. *Journal of Investigative Dermatology*, 132(3), 985-993.
32. Saeed, S., ul Haq, S., Sohaib, M., and Khan, A. N. (2017). Utility of Tc-99m MDP bone SPECT in evaluation of osseous involvement in craniofacial malignancies. *Journal of Cranio-*

Maxillofacial Surgery, 45(11), 1815-1819.

French Academy of Science: Problems associated with the effects of low doses of ionizing radiation'. *Journal of Radiological Protection*, 18(4), 243.

33. Santos, J. S., Uusi-Simola, J., Kaasalainen, T., Aho, P., and Venermo, M. (2020). Radiation Doses to Staff in a Hybrid Operating Room: An Anthropomorphic Phantom Study with Active Electronic Dosimeters. *European Journal of Vascular and Endovascular Surgery*.
34. Stabin, M. G. (2007). *Radiation protection and dosimetry: an introduction to health physics*. Springer Science and Business Media.
35. Suliman, I. I., Salih, L. H., Ali, D. M., Alaamer, A. S., Al-Rajhi, M. A., Alkhorayef, M., and Bradley, D. A. (2019). Occupational exposure in nuclear medicine and interventional cardiology departments in Sudan: Are they following radiation protection standards?. *Radiation Physics and Chemistry*, 160, 100-104.
36. Suliman, I. I., Salih, L. H., Ali, D. M., Alaamer, A. S., Al-Rajhi, M. A., Alkhorayef, M., and Bradley, D. A. (2020). Reprint of "Occupational exposure in nuclear medicine and interventional cardiology departments in Sudan: Are they following radiation protection standards?". *Radiation Physics and Chemistry*, 167, 108556.
37. Taleb, J., Janier, M., Bonazza, P., Roux, P., Miladi, I., Goutain-Majorel, C., ... and Kryza, D. (2013). Radiation dose measurements for staff members involved in holmium-166 preclinical trial. *Radiation measurements*, 58, 75-78.
38. Teles, P., Trincão, M., Alves, F., Antunes, V., Calado, D., Cantinho, G., and Isidoro, J. (2020). Evaluation of the Portuguese population exposure to ionizing radiation due to x-ray and nuclear medicine procedures from 2013 to 2017. *Radiation Physics and Chemistry*, 172, 108762.
39. Tsoulfanidis, N. (2010). *Measurement and detection of radiation*. CRC press.
40. Tubiana, M. (1998). The report of the

Figure 1. The scheme of exposure rate collecting data process using “radiation alert detector”.

Figure 2. Radiation dose rate curves ($\mu\text{Sv} / \text{hr}$) against detector distance variations (mm) for Cs-137 radioactive contamination measurement

Figure 3. Radiation dose rate curves ($\mu\text{Sv} / \text{hr}$) against distance variations (mm) for Cs-137 radioactive gamma measurement

Figure 4. Graph of the relationship between the contamination detector dose rate with the experimental gamma detector