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Radiation Safety Evaluation: Leakage and Dose Rate Distribution of a Laboratory X-Ray System

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ABSTRACT

Purpose of the study: This study aims to measure and analyze potential radiation leakage and dose rate distribution around the Phywe X-ray unit in an educational physics laboratory using a survey meter, in order to evaluate safety conditions and support improved radiation protection for users.

Methodology: This study employed a PHYWE X-ray Unit, survey meter (Geiger-Müller type), tape measure (Stanley 5 m), and digital stopwatch (Casio HS-3V). The method included literature review, experimental multi-point radiation leak measurement, repeated exposure timing, and dose rate mapping. Data were processed using Microsoft Excel for tabulation and graphical analysis.

Main Findings: Radiation intensity was 0 µSv/h at most measurement points. Detectable values occurred at 200 cm (261.12 µSv/h) and 300 cm (67.32 µSv/h), showing decreasing intensity with increasing distance. Dose rates were 36.72 µSv/h at 150 cm and 276.42 µSv/h at 650 cm. Results indicate dominant low exposure levels with variations influenced by distance, scattering, shielding, and measurement geometry.

Novelty/Originality of this study: This study provides systematic multi-point radiation leakage mapping of an educational-scale Phywe X-ray unit in a non-clinical laboratory setting. It generates empirical dose distribution data rarely reported for teaching laboratories, verifies inverse square behavior under real conditions, and reveals deviations caused by scattering and shielding, thereby advancing practical radiation safety knowledge beyond clinical-focused studies.

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1. INTRODUCTION

Radiation is the emission of energy through matter or space in the form of heat, particles, or electromagnetic waves (light/photons) from a radiation source. Several sources of radiation exist in our daily lives, including televisions, lighting, food heating devices (microwave ovens), computers, CT scans, mobile x-rays, and others [1]-[3]. Radiation is generally divided into two categories: ionizing radiation, which can cause ionization (the formation of positive and negative ions) when interacting with matter [4]-[6].

Non-ionizing radiation is a type of radiation that does not cause ionization when interacting with matter. Types of ionizing radiation include alpha particles (α), beta particles (β), gamma rays (γ), x-rays, and neutrons

[7]-[9]. Non-ionizing radiation includes radio waves, microwaves, infrared rays (which provide energy in the form of heat), visible light, and ultraviolet light [5]-[10]. The use of radioactive substances (α, β, γ, and x-rays) is part of nuclear technology whose benefits are being realized relatively quickly by humans [11]-[13]. This is because radioactive substances have specific properties not found in other elements [14]-[16]. By exploiting these radioactive properties, many complex problems can be simplified, making them easier to solve [17], [18].

One property of radiation is its ability to penetrate solid objects [19], [20]. This property is widely used in radiography, which involves photographing the interior of an object using nuclear radiation such as X-rays, α-rays, β-rays, γ-rays, and neutrons. The resulting images are recorded on X-ray film. In the modern physics laboratory of the Physics Department, Faculty of Science and Technology, UIN Alauddin, there is an X-ray unit used in practicals. To date, there has been no investigation into possible radiation leaks in this device, and it is not housed in a dedicated room. Despite its significant benefits, the radiation emitted by X-ray sources also has negative effects and is very dangerous for humans if used in very high doses or with increased exposure frequency, as X-rays are a source of ionizing radiation that is invisible and cannot be felt at that time.

Anies' [21] research, written in his book "Electrical Sensitivity," states that mobile phones can be harmful to human health due to the radiation they emit, even though the radiation is relatively small. Furthermore, Phywe X-ray units, which are a highly dangerous radiation source, despite their relatively low power, require research to prevent potential radiation leaks, given their significant potential for human exposure [22]. Therefore, to prevent radiation leaks, which are harmful to health, particularly for Phywe X-ray unit users, potential leaks will be measured so that users can feel safe and comfortable using Phywe X-ray units.

Although numerous studies have addressed radiation dose and leak measurements in clinical radiology installations and the effectiveness of radiation protection in X-ray examination rooms, studies specifically evaluating the potential for leaks and dose distribution in educational laboratory-scale X-ray units such as Phywe X-ray units are still very limited. Most previous studies have focused on hospital radiology installations and leak assessments in radiology rooms with industry-standard designs and protections, such as measuring radiation exposure in general radiology rooms and the effectiveness of radiation room shielding in large medical facilities, demonstrating dose distribution patterns and shielding effectiveness in a formal clinical setting [23]. Other studies have also examined radiation leakage from conventional X-ray machines to ensure safe operation and compliance with regulatory dose limits [24]-[26]. However, studies that map radiation dose distribution in detail around educational X-ray units, which are often located in open spaces without complete radiation shielding, are still lacking or have not been widely published in reputable international literature. This gap makes this study important, as it provides real-world empirical data on radiation leakage rates and distribution in educational laboratory environments, which can serve as a basis for more effective radiation protection evaluations and improve user safety outside of traditional clinical contexts.

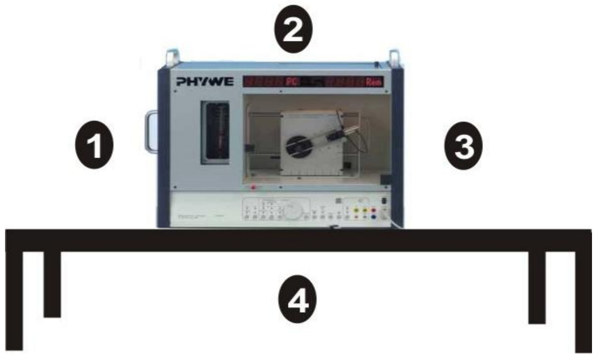
The novelty of this research lies in its experimental approach, which systematically evaluates radiation leakage and dose rate distribution in an educational X-ray unit (Phywe X-ray unit) in a physics laboratory environment not designed as a dedicated clinical radiology suite. Unlike previous research, which generally focuses on high-power medical radiology installations with formal protection standards, this study integrates multi-point mapping at varying distances in a single real-space configuration to simultaneously analyze the effects of distance, scattering, and shielding on dose distribution. In addition to verifying the validity of the inverse square law in an educational laboratory context, this study also identifies empirical deviations due to realistic geometric and environmental conditions. Thus, this study provides novel, experimentally based radiation safety data on educational-scale X-ray systems, a topic rarely discussed in the literature, and provides a scientific basis for evaluating and improving radiation protection standards in physics teaching laboratories.

This research is urgent because the use of X-ray units in educational laboratories without measurable radiation leakage evaluations potentially poses exposure risks to students and faculty. In addition, the availability of empirical data regarding dose distribution in educational-scale X-ray systems is very important as a basis for strengthening radiation safety standards and making more effective protection policies in academic environments. The purpose of this study is to examine and analyze the possibility of leaks in the Phywe X-ray unit equipment in modern physics laboratories to provide user safety with a survey meter. With the benefits of this study, it is hoped that the possibility of radiation leakage from the Phywe X-ray unit tube in modern physics laboratories will be prevented. As well as providing safety and comfort for Phywe X-ray unit users..

2. RESEARCH METHOD

This study used several instruments, namely the Phywe X-ray unit, survey meter, tape measure, and stopwatch, to ensure accurate and safe measurements. The research procedure began with a literature review on X-rays, radiation, and related safety principles. Next, all tools and materials were prepared according to the research needs. The next stage involved inspecting and measuring potential radiation leaks in the Phywe X-ray unit tube using a survey meter, which was carried out at specific points according to the measurement plan, to ensure operational safety and the validity of the research data.

View from the Front



View from Above

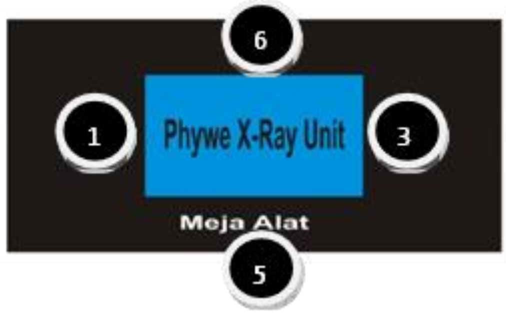


Figure 1. Leakage measurement points

After the initial measurements, the radiation data obtained were systematically recorded using a meter and stopwatch to determine the distance and duration of exposure. Measurements were repeated at each predetermined point to ensure consistency and accuracy of the results. All data were then analyzed to evaluate the level of radiation leakage and the effectiveness of the safety measures implemented on the Phywe X-ray unit. These measurement results form the basis for radiation safety recommendations and the planning of safe operational procedures for users and the laboratory environment.

3. RESULTS AND DISCUSSION

This section presents the results of radiation measurements conducted at six main points around the X-ray source and at several additional areas within the room to detect possible radiation leaks. The data is presented systematically in tabular form based on varying measurement distances and times, allowing for a more comprehensive analysis of radiation distribution patterns.

The following presents the results of radiation intensity measurements at various distances from the molybdenum X-ray source.

Table 1. Measured X-Ray radiation intensity of mo target as a function of distance

No	Measurement Point	Distance (cm)	Time (s)	Irradiance (µSv/h)
1.	Point 1	100	60	0
		200	60	0
2.	Point 2	100	60	0
	Point 3	100	60	0
		200	60	261.12
		300	60	67.32
		400	60	0
		500	60	0
3.	Point 4	45	60	0
4.	Point 5	80	60	0
5.	Point 6	100	60	0
		200	60	0

Based on the measurement results shown in Table 1, several measurement points showed very low or undetectable radiation intensity (0 µSv/h), indicating that most areas were below the sensitivity of the measuring instrument or under very low exposure conditions. Significant radiation values were only detected at distances of

200 cm (261.12 µSv/h) and 300 cm (67.32 µSv/h), and the intensity decreased substantially with increasing distance. This pattern is consistent with the principle of the inverse square law, which states that radiation intensity decreases proportionally with the square of the distance from the source, because the radiant energy is spread over a larger surface area as the distance increases. In the context of X-ray radiation and clinical applications of radiation, this law remains the basis for estimating the dose distribution with distance in a barrier-free medium [27].

In addition to the decrease in intensity due to distance, the undetectable radiation at several other measurement points can also be explained by the effectiveness of the radiation protection (shielding) and scattering systems. Scattering of radiation that occurs outside the main beam path often results in very low or undetectable intensities, especially when the barrier or shielding structure has been designed effectively. This scattering phenomenon has been reported in studies of X-ray dose distribution measurements in radiology rooms, where scattered radiation contributes to small variations at certain measurement points [28].

Overall, these results indicate that radiation exposure at most points is in the low and safe category, with variations influenced by distance from the source, protection efficiency, and direction of radiation emission, in accordance with the principles of distance, shielding, and time in X-ray radiation safety strategies to ensure that off-target exposure remains within safe limits for workers and the surrounding environment [29].

Tabel 2. Radiation Dose Rate at Different Distances

No.	Measurement Point	Distance (cm)	Time (s)	Dose Rate (µSv/hour)
1	Point 1 and 6	150	60	36.72
2	Point 3 and 6	650	60	276.42

Based on the measurement results in Table 2, a significant difference in radiation dose rates is observed between the two measurement points. At a distance of 150 cm (Points 1 and 6) with an exposure time of 60 seconds, the measured dose rate was 36.72 µSv/hour, while at a distance of 650 cm (Points 3 and 6) with the same exposure time, the measured dose rate was 276.42 µSv/hour.

Theoretically, the relationship between radiation intensity and distance is explained by the inverse square law, which states that radiation intensity is inversely proportional to the square of the distance from the source [30], [31]. This means that as distance increases, radiation intensity should decrease significantly because the radiant energy spreads over a larger area. This principle is the primary basis of radiation protection systems, particularly strategies for controlling exposure through increasing distance.

However, Table 2 shows that the dose rate at a distance of 650 cm is actually higher than at a distance of 150 cm. This indicates that the distribution of radiation in the field is not solely influenced by the geometric distance from the source. One factor that can explain this phenomenon is the contribution of scattered radiation. Scattering occurs when X-ray photons interact with surrounding material and are reflected in various directions, thereby increasing the dose rate at a given point even though it is located farther from the primary source [32]. In clinical and laboratory practice, scattered radiation is often the dominant component of exposure outside the primary beam.

Furthermore, the influence of shielding also needs to be considered. The presence of shielding material between the source and the measurement point can reduce the detected dose rate at certain locations, while other locations with more open scattering paths may exhibit higher dose values. The principle of shielding's effectiveness in reducing radiation exposure has been explained in radiation safety guidelines, which emphasize the importance of a combination of distance, time, and material protection in controlling exposure.

Thus, the results in Table 2 indicate that dose rate variation is influenced by a combination of distance, scatter, shielding, and measurement geometry, rather than distance alone. This interpretation is consistent with the basic principles of radiation protection, which state that dose distributions in real environments are complex and highly dependent on the physical conditions and configuration of the measurement room.

The findings of this study indicate that the intensity and dose rate of radiation decrease significantly as the distance from the source increases, following the inverse square law, where the radiation intensity (dose rate) is inversely proportional to the square of the distance from the radiation source a consequence of the inverse square law described in the literature on medical radiation protection and radiation physics. For example, the principle for medical radiation exposure states that exposure is reduced to one-quarter when the distance from the source is doubled, which is used as the basis for radiation protection in clinical radiology practice [33]. In addition, studies related to the distribution of scattered radiation in the X-ray examination environment report that scattered radiation contributes to the dose around the source, making the dose distribution in the radiology room inhomogeneous and affected by geometric factors of the room and surrounding objects [30]. The finding of anomalous increases in dose rates at specific distances in your study is consistent with these observations, indicating that scatter contributes to the pattern of dose decline when room size, measurement position, and radiation beam direction change. Thus, this study not only confirms the inverse square law well-established in the radiation protection literature but also supports empirical evidence that dose distributions at real sites are the result of a complex interaction between physical and environmental factors [33].

The novelty of this research lies in the systematic radiation measurement approach, conducted at multiple points and varying distances within the same spatial configuration, allowing for a comprehensive analysis of the simultaneous influence of distance, scattering, and radiation shielding on dose distribution. This research not only conceptually verifies the validity of the inverse-square law but also demonstrates empirical deviations due to realistic field conditions [34]-[36]. By integrating quantitative analysis of measurement results with interpretations based on radiation physics principles, this study provides a more contextualized picture of the behavior of X-ray radiation in a laboratory environment, a topic not yet discussed in detail in previous studies using similar measurement configurations.

The implications of this research for physics research are that it reinforces the importance of experimental studies in understanding real-world radiation distribution, particularly in the development of more effective radiation protection systems based on field data. For physics education, the results of this research can be used as contextual case studies in teaching the concepts of the inverse-square law, radiation-matter interactions, and radiation protection principles (distance, time, and shielding). The integration of real-world empirical data into the learning process has the potential to enhance students' conceptual understanding, as they not only learn theoretical models but also see how these theories interact with complex experimental conditions in the field [37], [38]. Thus, this research contributes to strengthening scientific literacy and analytical skills in physics education, particularly in modern physics and medical physics [39], [40].

Although this study provides an empirical picture of radiation dose distribution at various distances, several limitations need to be considered. First, the number of measurement points and the variety of geometric configurations of the room are still limited, thus not fully representing the three-dimensional spatial distribution of radiation. Second, the sensitivity of the measuring instrument to low intensities may affect the results at points with readings of 0 μSv/h, which does not necessarily indicate an absolute absence of radiation, but rather is below the instrument's detection threshold. Third, this study did not conduct numerical modeling or Monte Carlo simulations to quantitatively verify the contribution of scattered radiation, so interpretations regarding the influence of scatter remain analytical-descriptive. Furthermore, environmental variables such as wall material, object position within the room, and variations in X-ray spectral energy were not controlled in detail. Therefore, further research with a more comprehensive experimental approach and supported by computational simulations is needed to obtain a more precise and generalizable picture of the dose distribution.

4. CONCLUSION

This study concludes that the distribution of X-ray radiation intensity and dose rate from Mo (molybdenum) materials generally follows an inverse square law trend, where the intensity decreases with increasing distance from the source, as seen in the significant value at 200 cm (261.12 μSv/h) which decreases at 300 cm (67.32 μSv/h) and is low or undetectable at most other points. However, the finding of a higher dose rate at a distance of 650 cm compared to 150 cm indicates that the radiation distribution in real environments is not only influenced by geometric distance, but also by the contribution of scattered radiation, shielding effectiveness, and the configuration of the measurement room. Thus, this study confirms that the principles of distance, time, and shielding must be applied in an integrated manner in radiation safety evaluation. For further research, it is recommended to conduct measurements with a larger number of points and three-dimensional dose distribution mapping, use instruments with higher sensitivity, and integrate numerical simulations such as the Monte Carlo method to analyze the contribution of scattered radiation quantitatively and obtain a more precise and comprehensive dose distribution model.

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