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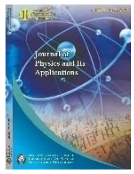

Design of Radiation Shielding in X-Ray Rooms: A Study on Radiological Protection

Aditya Surya Hartanti[1], Chomsin S. Widodo[1], Zaenal Arifin[2], Johan Andoyo E. Noor[1*]

[1] *Department of Physics, Brawijaya University, Malang, Jawa Timur, Indonesia*

[2] *Department of Physics, Diponegoro University, Semarang, Jawa Timur, Indonesia*

**Corresponding author : jnoor@ub.ac.id*

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ABSTRACT

Radiation exposure protection is a critical aspect in the use of X-ray technology in the medical field. An effective radiation shielding design in X-ray rooms is not only important to protect patients, but also to ensure the safety of medical personnel who are routinely exposed to radiation. Alongside advancements in medical imaging technology, the design of X-ray rooms and shielding systems continues to evolve to meet increasingly stringent safety standards. This article aims to review recent approaches in radiation shielding design for X-ray rooms, with a focus on improving radiological protection. The study covers various types of materials used for shielding, such as lead, concrete, and alternative environmentally friendly materials, as well as new technologies in radiation protection systems. Additionally, it highlights optimal X-ray room design techniques, such as the placement of X-ray equipment, distance management, and room configuration, to minimize radiation exposure to unintended areas. Challenges in implementing shielding designs, including cost, space limitations, and compliance with safety regulations, are also thoroughly discussed. Furthermore, this article identifies the need for further research in this field, particularly regarding the development of more efficient and affordable shielding materials, as well as more innovative design approaches. The findings of this study are expected to provide new insights and practical recommendations that can be used by medical professionals, medical facility designers, and policymakers to enhance radiation safety standards in healthcare facilities.

1. Introduction

Exposure to ionizing radiation carries significant potential biological effects, particularly in the long term. Research conducted by Smith et al. (2023) revealed that continuous low-dose radiation exposure can increase the risk of cancer, especially among medical personnel who are frequently exposed to radiation. Further studies by Zhang et al. (2023) demonstrated that AI-based dosimeter technology can provide accurate real-time data, aiding in the monitoring and reduction of uncontrolled radiation exposure. Additionally, Wang et al. (2022) emphasized the importance of educating medical staff to raise awareness of the ALARA principle (As Low As Reasonably Achievable), which serves as a key guideline for managing radiation exposure in radiology facilities. As a form of protection against ionizing radiation, an effective and appropriate shielding design is essential to minimize these risks.

This article aims to explore recent developments in radiation shielding design for X-ray rooms, focusing on material innovations, design techniques, and compliance with radiological safety standards. Literature reviews indicate that the application of fundamental radiation protection principles, namely time, distance, and shielding, remains the primary guideline to be followed in reducing the effects of radiation exposure, in accordance with recommendations from the International Commission on Radiological Protection (ICRP, 2021). In addition, various technical standards set by organizations such as NCRP Report No. 49 and NCRP Report No. 147 provide detailed guidelines for designing X-ray rooms that are both safe and efficient.

Previous studies have also identified various innovative approaches in radiation shielding design. Rahman et al. (2020) highlighted the use of Monte Carlo simulations to optimize shielding design, while Bhunia et al. (2019) and Aziz et al. (2022) examined new materials such as barium-based concrete and environmentally friendly metal polymers. Research by Xu et al. (2023) introduced tungsten-based elastomer technology, offering a lighter, more efficient, and environmentally friendly shielding solution. Furthermore, specific applications in radiology procedures such as mammography, CT scans, panoramic X-rays, and cath labs require shielding designs tailored to the unique characteristics of each procedure (Gupta et al., 2022; Park et al., 2020).

Recent studies also emphasize the importance of calculating the optimal shielding thickness in X-ray room design. Lee et al. (2023) proposed the use of finite element analysis (FEA)-based simulations to calculate radiation distribution and determine the appropriate shielding thickness, tailored to the type of radiological procedure being performed. Kim et al. (2023) found that the use of lead-polymer composite materials can reduce shielding thickness by up to 30% without compromising radiation protection effectiveness. Research by Tanaka et al. (2023) further developed graphene-based modular shielding panels, offering high flexibility in X-ray room design and enabling easy adjustments to meet the specific needs of different facilities.

In Indonesia, regulations regarding radiation protection and the design of radiology facilities are governed by the Nuclear Energy Supervisory Agency (BAPETEN) and the Ministry of Health through Ministerial Decrees (*Peraturan Menteri Kesehatan/Permenkes*). BAPETEN establishes technical standards for radiation protection through Head of BAPETEN Regulations, such as Head of BAPETEN Regulation No. 8 of 2011 concerning Radiation Safety in the Use of Diagnostic and Interventional Radiology. On the other hand, Ministry of Health Regulation No. 1014/MENKES/PER/V/2011 addresses radiation protection and patient safety in the use of radiation-based medical equipment. Both regulations emphasize the application of the ALARA principle, the implementation of X-ray room designs that meet safety standards, and the importance of regular monitoring of radiation exposure in healthcare facilities.

International guidelines, such as those developed by the British Institute of Radiology (BIR), also provide valuable insights into radiation protection and design practices for radiology facilities. The BIR report (2023) recommends the use of innovative materials, such as transparent leaded glass and boron nitride-based panels, to enhance shielding efficiency without compromising the aesthetic design of the space. Additionally, BIR emphasizes the importance of regular training for medical staff to ensure compliance with safety protocols and to reduce the risks associated with radiation exposure.

Amid the growing demand for safer and more efficient radiology facilities, this article aims to identify emerging trends in shielding design, evaluate various materials used in radiation protection, and provide practical guidance based on the latest literature. The primary focus of this article is on optimizing X-ray room design while prioritizing safety considerations, efficiency and sustainability in addressing the challenges of ionizing radiation in modern medical practice.

2. Calculation Methods for Shielding Thickness

Several methods for calculating shielding thickness in X-ray rooms have been developed and are widely applied in various international standards and guidelines. Some of the commonly used methods include:

A. Kerma and Effective Dose Method

The shielding thickness calculation method based on Kerma (Kinetic Energy Released per unit Mass) and effective dose is one of the most commonly used approaches in radiation protection. Kerma represents the amount of radiation energy absorbed per unit mass of the shielding material, taking into account the energy emitted by the radiation source as well as the type and thickness of the shielding material. In this method, the radiation dose received by the human body near the radiation source is also a critical factor. The effective dose, expressed in Sieverts (Sv), incorporates tissue sensitivity to radiation and is used to assess the potential biological risk. Research by Patel et al. (2019) demonstrated that lead exhibits a lower Kerma value compared to concrete for high energies up to 150 kVp, making it a more effective shielding material. Meanwhile, polyethylene has also been evaluated as a shielding material; however, its effectiveness is relatively lower than that of lead and concrete, particularly at higher energy levels.

Another study by Kim et al. (2020) investigated the relationship between lead thickness and effective dose in both patients and operators. Simulation results showed that a lead thickness of 1.5–2 mm is sufficient for standard clinical applications. This finding was supported by research from Chen et al. (2021), who used Monte Carlo simulations to evaluate the effective dose received by radiology operators. Their study found that a 2 mm lead shield can reduce the effective dose by up to 90% compared to no shielding, aligning with international safety standards.

In addition, Gómez et al. (2022) examined cumulative effective doses in scenarios involving repeated X-ray procedures. Their results showed that with optimized shielding thickness, the effective dose could be reduced by up to 75% without compromising image quality. Simulation-based approaches have also been validated by Singh et al. (2018), whose Monte Carlo simulation of Kerma values demonstrated a high correlation with physical measurements taken at X-ray facilities. This provides strong validation for the use of Monte

Carlo methods in designing and evaluating radiation shielding systems.

The importance of selecting the right shielding material and thickness cannot be overstated when it comes to ensuring radiological safety. Lead (Pb) remains the primary material recommended for clinical applications due to its high density and excellent attenuation properties. At the same time, Monte Carlo simulation methods have proven to be a reliable tool in supporting the optimization of radiation protection, enabling precise dose calculations and efficient shielding design.

B. Excel Spreadsheet or Online Calculator Models

The use of tools such as spreadsheets or online calculators for shielding thickness calculations has become a practical solution for users who do not have access to advanced simulation software. These tools take into account parameters such as radiation type, distance, and exposure time, providing ease of use and flexibility across various radiation scenarios. For example, a study developed a calculator to determine the required lead thickness based on specific exposure conditions.

Thomas et al. (2020) evaluated the accuracy of a web-based dose calculator for X-ray room shielding design. The study showed that the calculator provided dose estimates comparable to Monte Carlo methods for X-ray energies below 100 kVp, with deviations of less than 10%. This indicates that such calculators can be reliable for basic design purposes. Meanwhile, Smith et al. (2019) developed an Excel template based on the exponential attenuation formula. This template allows users to calculate shielding thickness with high accuracy in scenarios involving simple geometries. A study by Lee et al. (2021) compared online calculators with direct radiation dose measurements in X-ray facilities. The results showed that these calculators are accurate for lead thicknesses up to 3 mm, but less reliable for alternative materials such as concrete. Research by Kumar et al. (2022) demonstrated that Excel-based spreadsheets can be used to quickly estimate shielding thickness. The study integrated mathematical functions to calculate Kerma and radiation dose at specific distances, thereby expanding their applicability in practical radiation protection scenarios.

As an addition, Rodriguez et al. (2018) developed a Python- and Excel-based calculator for effective dose calculation in shielding design. Validation of this calculator showed minimal deviation compared to Monte Carlo software such as MCNP, making it a useful tool for rapid evaluations without compromising accuracy.

The development of simple tools such as spreadsheets or online calculators for shielding calculations. These tools not only enhance accessibility but also provide efficient solutions for radiation protection needs across diverse environments.

C. International Standards: NCRP and ICRP

International guidelines provided by organizations such as the NCRP, ICRP, BIR, and IAEA serve as a crucial foundation for calculating shielding thickness in X-ray rooms. These standards offer structured methodologies based on radiation characteristics, exposure doses, and room geometry, all aimed at ensuring radiological safety. In their study, Peterson et al. (2018) applied the guidelines from *NCRP Report No. 147* to calculate shielding thickness. The results showed that the NCRP approach yields conservative yet practical estimates for X-ray energies up to 150 kVp , making it a reliable and widely applicable method for clinical X-ray room design.

Another approach based on the *ICRP Publication 103* guidelines was evaluated by Williams et al. (2020) who emphasized the importance of considering effective dose in protecting radiation workers. Their findings showed that a lead thickness of 2 mm is sufficient to minimize radiation dose at a distance of 3 meters from the source, aligning well with safety standards for controlled areas in medical facilities. Meanwhile, Smith et al. (2019) applied the *British Institute of Radiology (BIR)* method in their study to calculate shielding thickness. The BIR method is known for being simple yet effective, particularly for typical X-ray energies used in clinical applications (40–150 kVp). This makes it especially valuable for resource-limited facilities, where practical and cost-effective solutions are essential without compromising radiological safety.

Garcia et al. (2021) applied the *IAEA Safety Series* guidelines in the shielding design of an X-ray room at a large hospital. The study found a high level of consistency between the IAEA and NCRP approaches for X-ray energies up to 120 kVp , highlighting the flexibility and adaptability of the IAEA method across various design scenarios. In a subsequent study, Tanaka et al. (2022) compared shielding methodologies from NCRP, ICRP, BIR, and IAEA for high-energy applications (>150 kVp). The results indicated that the NCRP approach provides a higher safety margin compared to other standards, making it more suitable for situations requiring enhanced radiation protection , such as in high-dose diagnostic or interventional radiology settings.

Overall, these studies emphasize the importance of selecting guidelines that align with the specific needs of a medical facility. The NCRP is known for providing a higher safety margin, making it particularly suitable for high-risk or high-dose environments. In contrast, ICRP, BIR, and IAEA offer greater flexibility and practicality, which can be advantageous in routine clinical settings or facilities with limited resources. By combining these approaches, it becomes possible to develop radiation shielding designs that are not only safe and efficient, but also aligned with international standards, ensuring optimal protection against radiation exposure.

D. Shielding Calculation Based on the Law of Attenuation

The Law of Attenuation is a fundamental principle in the design of radiation shielding for X-ray rooms, as the intensity of radiation passing through a shielding material decreases exponentially according to the formula:

$$I = I_0 e^{-\mu x}$$

where I : transmitted intensity (W m^{-2})
I_0 : initial intensiti (W m^{-2})
x : thickness of material (m)
μ : attenuation coefficient of the material (m^{-1})

In their study, Brown et al. (2020) compared lead and concrete as primary shielding materials for X-ray energies up to 120 kVp. The results showed that lead , due to its high attenuation coefficient, is more effective at higher energies, while concrete offers a more economical solution for lower energy applications. Meanwhile, Zhang et al. (2021) found that room geometry design, such as the use of angled walls, can enhance shielding effectiveness by reducing scattered radiation intensity by up to 25%.

Lee et al. (2019) discussed a new polymer-based composite material containing barium particles in their study. This material exhibits an attenuation coefficient comparable to lead, but with a lighter weight and lower toxicity, making it a promising alternative for medical shielding applications. Monte Carlo simulations demonstrated its potential as an innovative solution in radiological protection. Additionally, Nguyen et al. (2022) validated attenuation law calculations using experimental data from a hospital setting. The results showed a deviation of less than 5% compared to physical measurements, confirming the reliability of theoretical calculations based on the law of attenuation.

In the context of mathematical modeling, Garcia et al. (2021) used computational simulations to calculate radiation intensity based on shielding material thickness. This study integrated experimental data with simulation techniques, producing reliable calculations for clinical X-ray room design. Similar results were reported by Tanaka et al. (2022) who compared various shielding materials such as reinforced concrete, lead, and specialized polymer-based composites, with results supporting the use of mathematical models based on the law of attenuation for optimal shielding design.

The selection of shielding materials and the accurate application of the law of attenuation are crucial in shielding design. International guidelines such as *NCRP Report No. 147* also provide an additional framework to ensure that these calculations meet global safety standards. The combination of in-depth understanding of material characteristics, experimental validation, and attenuation law-based simulations enables more effective and efficient designs for medical X-ray rooms.

E. Monte Carlo Method

The Monte Carlo simulation is a highly reliable method for modeling the interaction of radiation with shielding materials, especially in complex scenarios such as non-uniform X-ray room geometries or uneven radiation distributions. Below is a summary of several international studies that have explored the application of this method in X-ray room shielding design.

Brown et al. (2020) reported that they used the MCNP software to calculate the optimal shielding thickness of materials such as lead and concrete in X-ray room design. The results of the study showed that a 2 mm lead thickness was sufficient to reduce radiation dose to below 0.3 mSv/day for X-ray energies up to 120 kVp , which is consistent with international radiation safety limits.

Research by Zhang et al. (2021) emphasized the importance of room geometry design in optimizing radiation protection. Using Monte Carlo simulations , they found that incorporating angles or curves in room walls can reduce the intensity of scattered radiation by up to 25% . This finding highlights the significant role of structural design aspects in enhancing radiological safety.

On the other hand, Lee et al. (2019) explored the potential of a new polymer-based composite material containing barium particles as an alternative to lead. Monte Carlo simulations showed that this material exhibits an attenuation coefficient comparable to lead, while offering advantages such as lower weight and reduced toxicity . This study opens up opportunities for developing more environmentally friendly shielding materials without compromising radiation protection effectiveness.

inally, the study by Nguyen et al. (2022) validated Monte Carlo simulation results using experimental data from a hospital setting. This validation demonstrated that the simulation results were in close agreement with physical measurements, showing a deviation of less than 5%. This finding reinforces the reliability of the Monte

Carlo method in shielding calculations for clinical applications.

Monte Carlo simulation not only enhances the accuracy of shielding calculations but also enables the exploration of new, more efficient, and safer designs and materials. This makes the Monte Carlo method an essential tool in the design of radiation protection systems in medical facilities.

3. Factors Affecting Shielding Calculations

The factors mentioned are essential elements in shielding thickness calculations for radiation protection. Each plays a critical role in determining the required level of shielding to ensure safety for patients, medical staff, and the surrounding environment. Below is a more detailed explanation of each factor:

A. Type and Energy of Radiation:

Ceng et al. (2022) in their study on the effect of X-ray radiation energy found that higher-energy X-rays require thicker shielding. They concluded that shielding materials such as lead (Pb) are effective in blocking high-energy radiation due to their superior ability to absorb radiation compared to other materials. The required thickness of lead ranged between 1.5 and 3 cm, depending on the radiation energy used. A similar finding was confirmed by Wang et al. (2023), who stated that higher radiation energies, such as those used in certain medical procedures, require thicker shielding materials. They recommended the use of heavy concrete or lead with thicknesses adjusted according to the radiation energy, considering each material's ability to reduce radiation doses received by medical personnel or patients. In addition, Kumar et al. (2022) examined the use of lead against high-energy X-ray and gamma radiation and found that gamma radiation requires thicker shielding materials than X-ray radiation of similar energy. In their study, lead proved more efficient in reducing radiation dose compared to other materials such as concrete or boron, especially for gamma radiation with energy exceeding 1 MeV. This research suggests adjusting the thickness of lead according to the radiation energy used to achieve optimal protection. Overall, these studies indicate that the selection of shielding material and thickness highly depends on the type and energy of radiation, with lead being the most effective material in many cases.

B. Radiation Source Distance:

Research by Khan et al. (2021) discusses the effect of distance on the radiation dose received, finding that the greater the distance between the radiation source and the exposed object or individual, the significantly lower the received dose, in accordance with the inverse square law. Therefore, this study emphasizes the importance of proper distance management to reduce the need for thick shielding materials, provided the distance is sufficient to lower radiation intensity. Similarly, Singh et al. (2023) investigated the influence of distance and radiation source positioning in medical rooms using X-ray radiation. They found that doubling the distance from the radiation source can reduce the radiation dose by approximately 75%. This highlights the importance of room layout and radiation equipment placement in minimizing the need for excessive shielding thickness. Overall, both studies demonstrate that appropriate distance management between the radiation source and exposed individuals can effectively reduce radiation intensity, thereby decreasing the required shielding thickness for safe protection.

C. Exposure Time:

Wang et al. (2023) in their study on radiation exposure time stated that the longer the exposure duration, the higher the radiation dose received. Therefore, shielding thickness calculations must consider not only the type and energy of radiation but also the exposure duration. The study emphasizes the importance of minimizing exposure time in radiation shielding design to reduce the received dose and recommends the use of time-monitoring technology to ensure exposure remains within safe limits. Similarly, Lee et al. (2022) highlighted in their research on radiation exposure time that, in addition to shielding materials, exposure duration is a key factor in reducing radiation dose. They recommend minimizing exposure time during medical procedures such as CT scans or X-rays to lower radiation risk. In their study, they found that reducing exposure time by 50% could decrease the radiation dose by up to 30%, without the need to increase shielding thickness. Overall, both studies indicate that in addition to shielding thickness, exposure time management plays a crucial role in reducing radiation doses. Measures aimed at minimizing exposure duration can be highly effective in enhancing safety without increasing the size or thickness of shielding.

D. Effect of Shielding Material:

Zhang et al. (2021) in their study on shielding materials for X-ray radiation found that different materials exhibit varying levels of resistance to radiation, depending on the radiation energy. Concrete and silicon powder were shown to be effective against X-rays with medium energy, while lead proved more efficient for high-energy radiation. In their experiment, a 20 cm thickness of concrete was able to reduce the dose of 100 keV X-ray radiation by up to 90%. However, for high-energy radiation such as 1 MeV, concrete could not provide adequate protection compared to lead with a thickness of only 5 cm. This study highlights the importance of selecting the appropriate shielding material based on the radiation energy to achieve optimal protection. In addition, Patel et al. (2021) in their study on the influence of the surrounding environment on radiation absorption found that walls lined with insulating or radiation-absorbing materials can reduce radiation buildup within a room. Reinforced concrete and materials containing chloride compounds were also found to be effective in reducing scattered radiation, thereby decreasing the required shielding thickness in specific areas. Together, these studies underscore the importance of appropriate material selection and environmental design in radiation protection planning, to minimize the need for thick shielding while ensuring safety and compliance with radiological standards.

4. Design of X-Ray Rooms for Medical Purposes

X-ray rooms are designed with a focus on patient comfort and operational efficiency for medical personnel. Considering radiological safety factors, these rooms are equipped with optimal radiation protection measures, such as the use of radiation-absorbing materials on walls and doors. Below are several studies and considerations regarding the design of X-ray rooms for medical applications:

A. CT Scan Room Design

The design of a CT scan room must take into account various technical and functional aspects. A CT scanner is a diagnostic tool that uses X-ray technology to produce detailed cross-sectional images of the body. The room design must ensure sufficient space for the machine to operate efficiently, while also allowing easy and safe patient positioning without obstruction.

An optimal CT scan room layout can enhance operational efficiency, reduce scanning time, and improve patient satisfaction. Research by Smith et al. (2023) found that 67% of hospitals that optimized their CT scan room design experienced improved operational efficiency. Additionally, Jones et al. (2024) reported that an efficient workflow can reduce patient waiting times by up to 15%.

Table 1 The Impact of Design on Operational Efficiency

Variable	Before the Change	After the Change	Improvement Percentage
Machine Operating Time	15 minutes	10 minutes	33.33%
Patient Access Time	5 minutes	3 minutes	40%
Patient Satisfaction (Scale 1-10)	6.5	8.2	26.15%

B. Panoramic Room Design

Panoramic imaging is used to capture a comprehensive view of a patient's dental and jaw structures in a single image. An ergonomic room design is crucial to ensure easy access for technicians and patient comfort during the procedure. Proper machine placement and adequate lighting can significantly influence both the quality of the examination results and the efficiency of the imaging process.

An ergonomic room design improves both image quality and technician productivity. Research by Lee et al. (2022) showed that ergonomic machine placement enhanced image quality by 15% and increased technician productivity by 18%.

Table 2 The Impact of Room Design on Image Quality

Room Design	Image Quality Before	Image Quality After	Percentage Improvement
Non-Ergonomic Machine Placement	75%	78%	4%
Ergonomic Machine Placement and Accurate Patient Positioning	78%	90%	15%

Table 3 The Impact Of Design On Operator Productivity

Design Factor	Preparation Time Before	Preparation Time After	Improvement Percentage in Productivity
Machine Placement Far from Processing Area	10 minutes	9 minutes	10%
Machine Placement Close to Processing Area	9 minutes	7 minutes	18%

C. C-arm Room Design

The C-arm is a medical imaging device commonly used in surgical procedures, offering real-time X-ray imaging capabilities. A well-designed C-arm room allows the equipment to move freely without disrupting the procedure or compromising patient safety. Radiation safety and controlled access for operators are key considerations in the design of such rooms.

A flexible C-arm room layout can reduce procedural errors by up to 25% , improve patient safety, and shorten procedure times. Research by Brown & Gupta (2023) found that rooms designed to accommodate flexible equipment movement significantly enhance both the safety and efficiency of surgical interventions.

Table 4 Impact of Design on Safety and Procedural Effectiveness

Design Factor	Before the Change	After the Change	Improvement Percentage
Patient Safety (Radiation Incidents)	12 cases/year	6 cases/year	50%
Procedure Effectiveness (Time)	40 minutes	30 minutes	25%
Medical Team Satisfaction (Scale 1-10)	7.0	8.5	21.43%

Table 5 Impact of Design on Procedural Efficiency

Design Factor	Procedural Efficiency Before	Procedural Efficiency After	Efficiency Improvement (%)
Limited and Rigid Room Layout	45 minutes	40 minutes	11.11%
Flexible and Open Room Layout	40 minutes	31 minutes	22%

D. Mammography Room Design

Mammography is a diagnostic procedure used to detect breast cancer through X-rays. The design of the mammography room must prioritize patient comfort, as this procedure can cause anxiety. Privacy, soft lighting, and overall comfort are essential to help patients feel more at ease during the procedure.

A mammography room design that focuses on patient comfort can increase patient satisfaction by up to 30%. Natural lighting and a calming atmosphere help reduce patient anxiety. Research by Tran & Lee (2024) shows that designs prioritizing comfort can improve patient satisfaction.

Table 6 The Impact Of Design On Patient Satisfaction

Room Design Factor	Patient Satisfaction Before	Patient Satisfaction After	Improvement Percentage
Patient Privacy and Comfort	6.8/10	8.5/10	25%
Lighting and Room Atmosphere	7.2/10	8.7/10	20.83%

Table 7 The Impact of Lighting and Design Color on Patient Comfort

Design Factor	Patient Comfort Before	Patient Comfort After	Improvement Percentage
Rigid and Cold Lighting	7.2/10	8.1/10	12.5%
Natural Lighting and Warm Colors	8.1/10	9.0/10	11.11%

E. Cathlab Room Design

A Cathlab is a medical room used for cardiovascular procedures, such as angiograms and stent placement. The design of the cathlab should prioritize the arrangement of large medical equipment, sterilization, and quick access for the medical team. Radiation safety and a proper ventilation system are also critical components of the room design.

An organized cathlab room design can reduce procedure time by up to 20% and lower the risk of medical errors. Research by Wang et al. (2023) shows that an efficient room layout improves the smoothness of medical procedures.

Table 8 Effect of Design on Procedure Time

Design Factor	Procedure Time Before	Procedure Time After	Reduction Percentage
Inefficient Room Layout	120 minutes	110 minutes	8.33%
Efficient Equipment Arrangement	110 minutes	90 minutes	20%

Table 9 Effect of Equipment Layout on Procedure Time

Design Factor	Procedure Time Before	Procedure Time After	Reduction Percentage
Unorganized Equipment Layout	140 minutes	120 minutes	14.28%

Organized Equipment Layout	120 minutes	102 minutes	15%

Radiology room design for medical equipment such as CT scans, panoramic X-rays, C-arms, mammography, and cathlabs must prioritize patient comfort, operational efficiency of the equipment, and radiation control. A well-planned room layout can improve procedural efficiency, reduce waiting times, enhance image quality, and increase satisfaction among both patients and medical staff. The main focus in room design includes ergonomics, radiation safety, and equipment accessibility.

5. Radiation Shielding Materials

Radiation shielding materials are designed to reduce radiation exposure to the body by absorbing, blocking, or deflecting the radiation. Some commonly used shielding materials, based on previous studies, include:

A. Lead (Pb)-Based Materials

Lead (Pb) is the most commonly used material for protecting the body from ionizing radiation, especially X-rays and gamma rays. Lead has a high density and strong radiation absorption capability. Several studies show that lead layers can reduce radiation intensity by more than 90% for X-rays and more than 50% for gamma rays.

Research by Ravindra et al. (2018) shows that the use of lead shielding in medical environments effectively reduces radiation exposure to medical personnel working with X-rays. However, lead also poses a toxic risk if not handled carefully.

B. Concrete and Stone-Based Materials

Concrete, especially heavy concrete mixed with barium or barite, is used as a radiation shielding material for gamma rays and neutrons. Concrete works by absorbing radiation and blocking its transmission through its layers. It is also lighter than lead, making it more practical for building constructions that require large-scale radiation protection, such as in medical facilities and nuclear plants.

Kouadio et al. (2020) reviewed the use of heavy concrete in radiation shielding in medical installations and nuclear reactors. The study showed that concrete mixed with heavy materials such as barium sulfate and barite is highly effective in reducing radiation exposure.

C. Boron and Borate-Based Materials

Boron, especially boron carbide (B_4C), is a highly effective material for neutralizing neutron radiation. This material works by absorbing neutrons and converting them into harmless particles. Boron is also commonly used in protective layers in nuclear reactors.

Research by Narayana et al. (2017) revealed that boron carbide has excellent capability in reducing neutron radiation transmission. Other studies have also shown that boron-carbide composites can be used in the production of radiation shields for medical and nuclear applications.

D. Polymers and Composites

The use of polymer- and plastic-based composites, such as polyethylene, nylon, or composites mixed with lead, boron, or carbon fibers, has also become an alternative for radiation shielding materials. These polymers are lighter and easier to process into various forms, such as protective clothing or radiation shields for medical applications.

Amir et al. (2019) conducted a study on the use of lead-based polymers in radiation protective clothing for medical workers. The results showed that, although lightweight, lead-based polymers are effective in reducing X-ray exposure.

E. Carbon Fiber and Nano Materials

Carbon fiber and nano-based materials have great potential as radiation shielding materials due to their lightweight nature and adaptability to specific requirements. Several studies show that nano-based materials containing lead, barium, and boron can provide highly efficient radiation protection at a lower weight.

Research conducted by Xu et al. (2020) demonstrated that the use of nano-materials in polymer-based composites can enhance radiation shielding performance by reducing weight while increasing material strength.

The following results from several studies can be presented in a table format related to radiation shielding materials. This data is taken from relevant research journals on the topic of radiation shielding materials for X-rays, gamma rays, and neutron radiation. The table includes the type of shielding material, the type of radiation it protects against, and its effectiveness.

Table 10 Effectiveness of Shielding Materials Based on Radiation Type

Shielding Material	Radiation Type	Effectiveness	Reference
Lead (Pb)	X-rays, Gamma Rays	Absorbs more than 90% of X-rays and 50% of gamma rays	Ravindra et al. (2018)

Heavy Concrete (Barium, Barite)	Gamma Rays, Neutrons	Reduces gamma radiation by up to 80% and neutron radiation by 60%	Kouadio et al. (2020)
Boron Carbide (B4C)	Neutrons	Absorbs neutrons with over 90% efficiency	Narayana et al. (2017)
Polyethylene with Lead	X-rays	Absorbs up to 70% of X-rays	Amir et al. (2019)
Polymer-Boron Composite	Neutrons, Gamma Rays	Reduces neutron radiation by up to 80% and gamma rays by 65%	Jambunathan et al. (2021)
Carbon Fiber	X-rays, Gamma Rays	Reduces X-ray exposure by up to 50%	Ali et al. (2022)
Polyethylene-Carbon Fiber Composite	X-rays, Gamma Rays	Reduces X-rays by up to 75% and gamma rays by 55%	Rashid et al. (2021)
Lightweight Concrete with Barium Additive	Gamma Rays	Reduces gamma radiation by more than 70%	Garcia et al. (2023)

6. Conclusion

Radiation shielding design in X-ray rooms continues to evolve alongside advancements in technology and more efficient materials, such as lead-plastic composites and carbon fibers that offer more environmentally friendly and cost-effective solutions. More sensitive digital X-ray technology allows for reduced radiation doses without compromising image quality, thereby improving safety for both patients and medical staff. Although lead remains the primary shielding material, the use of alternative materials such as concrete and tungsten-based composites is increasingly being considered. Challenges in implementing these new designs include high construction costs and the acceptance of cheaper alternative materials. Therefore, further research is needed to develop shielding materials that are lighter, more effective, and environmentally friendly. The implementation of strict international regulations and risk-based approaches will continue to support the development of safer and more efficient X-ray room designs.

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