Cardiac Catheterization Lab Operator Radiation Shielding Optimization and Redesign

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Date: 4/18/2022

Abstract

The aim of this project is to develop a more efficient, convenient, and cost-effective shielding system to be installed in a cardiac catheterization lab. As of the date of publishing, the Grady Hospital catheterization lab staff primarily use a small leaded-acrylic shield (45cm x 45cm x 1cm) fastened to the side of the C-arm. This current system is standard across many cardiac labs, due to its low cost and efficient protection from radiation . However these can be inflexible during complex procedures that require constant repositioning of the shield and C-arm. Furthermore, the absorption rate of a leaded acrylic shield reduces with higher frequency X-rays. A new floor-mounted rolling shield is proposed with a more absorbent Tungsten- Bismuth alloy. The support structure builds on existing rolling shield systems, with additional stability and wrist support features. The new shielding material is proposed as an effective cost-efficient alternative that prevents almost 100% of high energy ionizing radiation. Powder metallurgy and die casting are compared as viable manufacturing methods for the shield, from which the sintering process in powder metallurgy is deemed the most efficient manufacturing method, in terms of quality and cost.

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1 Introduction

During any medical procedure involving radiotherapy, the two stakeholders involved during such procedures are the patient and the operators. The focus of this report is on radiation exposure to operators. Interventional cardiologists must carry out procedures that emit large amounts of damaging X-ray radiation, causing these professionals to be the most exposed in the medical workplace. There are existing safety measures in place that aim to reduce this exposure, however in many instances this reduction is either minimal, or the reduction practices interrupt/limit the staff's ability to operate. Prior to the procedure, operators commonly don leaded aprons and glasses as additional protection.

2 Radiation Dangers Occuring in Cath. Lab

Interventional procedures in the catheterization lab can involve heavy doses of high-energy radiation. Below is a list of common procedures performed in the Cath Lab [1]:

- Balloon angioplasty
- Coronary and left ventricular digital angiography
- Coronary intravascular ultrasound
- Right and left heart catheterization
- Rotational artherectomy
- Stent implantation
- Thrombectomy

The procedures with the highest radiation exposure are structural or valvular cardiac procedures followed by peripheral vascular procedures [2]. Of the structural cardiac procedures, fluoroscopy time and radiation dose are greatest for percutaneous transcatheter aortic valve implantation, transcatheter mitral-valve approximation with MitraClip, and left atrial appendage closures [2]. There are longer case times and higher radiation exposures as operators are still getting experience with the procedures [2]. Studies are mixed when radiation dose in structural cardiac procedures were obtained and compared to percutaneous intervention; they were either found to be significantly greater or similar [2]. On the other end of the spectrum, pacemaker insertion and electrophysiology ablation procedures were associated with the least radiation dose [1].

The most common ionizing radiation used in a cath-lab occurs in the X-ray field, typically with wavelengths in the range of 0.01 nm up to 10 nm [3]. This corresponds to a photon energy range of 100 keV down to 100 eV [3]. The well-documented dangers of such X-ray ionizing radiation arise from the radiation having enough energy to potentially damage DNA [4]. These can lead to many health risks to exposed persons, including a small increase in likelihood of developing cancer in later life, and tissue effects (occurring at relatively high levels of radiation exposure) such as cataracts, skin reddening, and hair loss [4].

Radiation exposure in fluoroscopy equipment like C-arms comes from two main sources- “scatter” radiation that bounces off the patient's body and “leakage” radiation from the X-ray tube [5]. Of the two sources of exposure, scatter radiation varies considerably more and is the higher contributor to overall exposure [5]. With scatter radiation bouncing off the bed and patient, the most important body parts of the operator that need to be protected are the torso and head. Radiation calculations have shown that X-ray radiation waves incident on the operator’s body at an angle greater than 50 degrees do not get absorbed very well, and are thus not as harmful [6]. Hence all body parts approximately from the knees of the operator to the head must be protected.

3 Review of Existing Design in Grady Hospital

The current shield design at Grady’s hospital has an estimated size of 45cm by 45cm by 1cm (length by width by thickness). This shield is attached to the top of the C-Arm using 1 or 2 thin metal rods, and can be slid to certain distances, however, is restricted to movement in one direction – sideways. The design is a rectangular shield made from lead, which is located at a level which protects only the chest and above of the standing operator. The adjustable height and sideways position help provide only a certain amount of protection for the operator.

The current design at the hospital is easy to manufacture in bulk, as it has a standard shape and may be slightly customized to include handholes in certain positions to aid the work of the operator.

However, the protection provided by such designs is not enough as the operator has a lot of exposure from their chest and below, considering a lot of the radiation is scattered from below the table, upward, towards the image intensifier.

4 Review of Existing Designs Worldwide

The radiation shielding tools and practices in catheterization labs vary around the world. Depending on a myriad of factors (such as cost/access to resources, production and supply chain accessibility, size of lab, typical procedures carried out, other current protective gear and measures in place), hospitals choose amongst a variety of radiation shields already on the market. While these shields are available in a variety of shapes and sizes, the focus of this report is on the flexibility posed by the mounting of the shield, and the material that these shields are typically composed of.

1. Floor mounted (rolling/fixed)

Floor mounted shields are the most commonly found shields, mostly due to its maneuverability and cheap manufacturing costs. It is a flexible design that involves a vertical panel mounted on top of a fixed base or a mobile base with at least four wheels. These types of shields have already been explored, and patents already do exist. An example of one such design is a rolling shield which is placed across and above the patient throughout procedure [7].

2. Ceiling-suspended shields

Ceiling-suspended shields are typically made of transparent leaded plastic that are readily adjustable during the procedure. Precise positioning of this is the key in significantly reducing operator exposure. There is a gap in protection created by the patient contour cutout and to minimize this, the upper body shield should be located far from the scatter source and near the operator. For example, in femoral artery access sites, it should be positioned just cephalad to the groin and as close as possible to the patient surface. Throughout the procedure, frequent repositioning of the upper body shield should be kept in mind as the table is moved to maintain effective protection [2]. An example of such a design is a ceiling-suspended drape hanging across and above the patient that houses a cavity sized to receive the upper portion of the shield [8].

3. Table-suspended curtains and drapes

The under-table X-ray tube gives off significant scatter radiation that is not usually covered by lead aprons. Table-suspended drapes or lead curtains between the X-ray tube and the operator provide protection from it. In the extended protective shield under table to reduce operator radiation dose in percutaneous coronary procedures (EXTRA-RAD) study, the use of under-table anti-radiation shields (drapes or curtains) resulted in lower radiation dose exposure at the pelvic and thorax level of the operators [2]. In another study, installation of protective curtains has been shown to lead to a radiation dose reduction of as much as 64% [2]. While a specific patented design may not exist, this design has been implemented as an optimization of radiation protection in some procedure rooms [9].

Material Choice:

Based on current safety handbooks, textbooks, and articles around the world, the most common material used for a transparent shield is leaded acrylic. Lead is widely seen as an effective and cheap means of absorbing high frequency radiation, such as X-rays.

5 Suggested Shield Shape

Some of the main factors considered while designing the shields include:

1. Protection level that is provided by the design - This would be the most important factor. All of the designs would provide more protection than the current designs are providing, and the reasons are discussed under each design.
2. Manufacturability of the design – Evaluate the ease of manufacturing using common methods and providing possible alternatives if required.

3. Stability of the design – This addressed weight distribution on all sides of the shield. The design must be able to stand on its own and move around without toppling over or bending.
4. Mobility of the Design - The shield design is portable and not attached to the C-arm, allowing movement in all directions thus providing control to the operator giving them a chance to move the shield according to their comfort and still protect themselves.
5. Cost of manufacturing – Being the last consideration, this factor was kept in control in order to allow for bulk manufacturing and greater profits from selling the designs.

Rectangle design

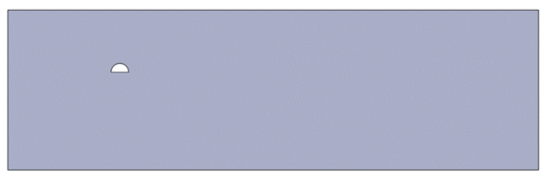


Figure 1: Rectangle Design

It is a rectangular shaped shield, as shown in Figure 1, with a semi-circle cut out to fit the patient's hand through for interventional procedures. It is flat, easy to manufacture, easy to support with support structures, cost effective but most importantly very effective at providing protection to the operator from the scatter radiation.

Oval design

Figure 2: Oval Design

As shown in Figure 2, it is a regular oval shaped shield with a semi-circle for the patient's hand. It is flat and would be effective in reducing the radiation exposure to the medical officers. However, it would not be very easy to manufacture considering the possible methods of die casting, where a mold would be required, and making a mold of this shape would not be very easy or cost efficient. Additionally creating support structures for this shape wouldn't be the easiest as the weight is not constant in all directions.

Curved Rectangle Design

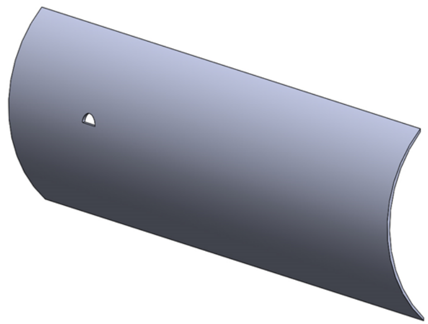


Figure 3: Curved Rectangle Design

Curved designs may do a better job at absorbing the radiation and thus providing better protection due to the larger range of distance they protect over and direction that they reflect the scatter radiation in. As seen in Figure 3, this design is a regular rectangle that is curved, it covers a large amount of area reducing exposure, however, comes with a lot more problems than solutions. The first being the fact that it is curved, even though the curve may not be as much, it makes the design unstable, and it may take up more space than required in an already congested working environment. The second issue with this design would be the mold not being the most precise in terms of the curvature required, thus may lead to under-curving or overcurving of the shield. Plus, a curved mold would be more expensive than just a flat design.

Ice-Cream Model

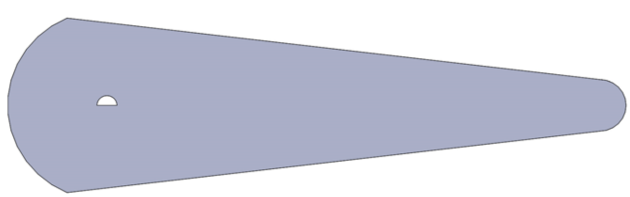


Figure 4: Ice-Cream Model

This is a flat shield with a semi-circle cut out to fit the patient's hand. As modeled in Figure 4, the design has a large semi-circle on the left side, towards the patient's head and hand, and gradually decreases in size as it moves towards the patient's legs. This helps protect much more from the radiation that is towards the top and center of the bed, as the main points of radiation are towards the upper body of the patient (right below the image. intensifier) The main problems found with this were stability and cost. The shaping of the mold to this shape would increase the cost of manufacturing and the design would be difficult to support due to the uneven weight distribution, as one side would require more support compared to the other increasing the overall weight of the model.

Rectangle with a single side curved

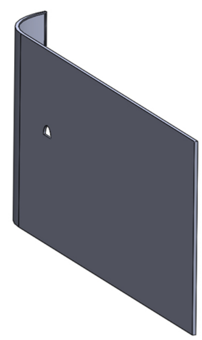


Figure 5: Rectangle with a single side curved

This design would be curved towards the top side of the bed, as shown in Figure 5, bending over the patient's head. This design would provide protection, in terms of absorbing the radiation and even deflecting some away from the medical officer. However, concerns with this model include the limitations in the movement of the C-arm that is brought about. Since this would curve over the patient's head, it would become an obstacle in the way of the C-arm. The second problem would be the cost. It would be difficult to find a mold of that shape and other methods like joining the curve and rectangle after they have been molded may lead to issues like gaps in the shield reducing the effectiveness of the shield. It can be supported well from both sides using standard support structures.

Rectangle with both sides curved

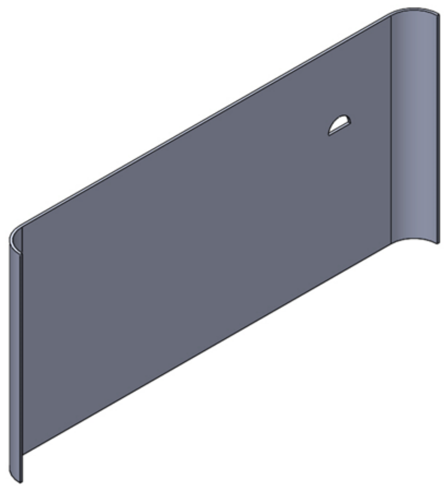


Figure 6: Rectangle design with both sides curved

The design is shown in Figure 6. This would allow a great amount of radiation to be deflected away from the operator. The design is stable in terms of weight distribution and can be easily supported from both sides using standard support structures. It would be effective as it provides the necessary protection to the medical officers, however the extra molding cost and manufacturing effort doesn't make it the ideal shape.

House Design

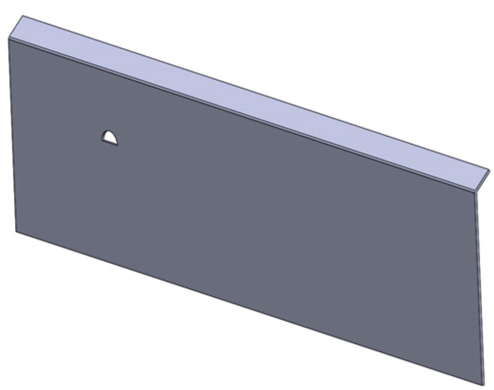


Figure 7: House Design

This design is shaped like the side of a house, with a wall and a slanting rooftop. This design hovers over the body of the patient and deflects any radiation that is released towards the top of the lab, reducing the exposure to the medical officers. As seen in Figure 7, this design would interfere with the movement of the C-arm. The second issue would be the stability of the design, as there is additional weight at the top that is slanting, shifting the center of gravity more towards the inside of the shield. Creating support structures would help, but may not be effective considering it would be hard to support the top slanting part. The cost and difficulty of manufacturing further reduce the desirability of this design.

The design that we chose to go with was the Flat Rectangular Design, shown in Figure 8. It is simple, thus making it possible to manufacture easily in bulk, such that the time of manufacturing would not be as high as we would have a standard rectangular mold of a particular size with a semi-circle cut out which is much easier to make compared to the mold required for the other designs. The second reason is stability. The weight is even throughout the shape, thus allowing for equal support structures on each side of the design to allow for sufficient stability for the shield. Most importantly it provides maximum protection as we believe that it covers the maximum area above, below and towards the sides, allowing for maximum radiation absorption and minimum exposure for the medical officer.

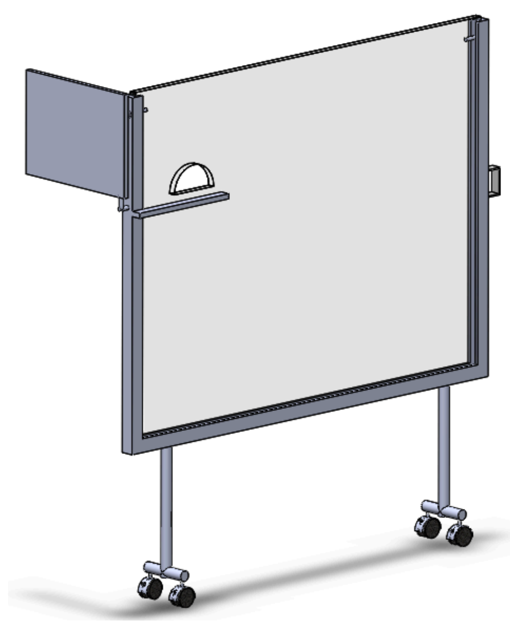


Figure 8: The chosen design: Flat Rectangle Design

6 Design Specifications

Described above were the general reasons for choosing the Flat Rectangular shaped shield. This section outlines the specifics of the design made. The design was initially designed by hand in the ideation stage, and then modeled using Solidworks. The units used throughout the ideation and modeling stage were centimeters.

Shield

The shield has dimensions of 132cm x 102cm x 2cm (length x height x width/thickness). The chosen height, length and width cover a sufficient area, thus providing maximum radiation protection. The shield contains a semi-circular cut-out to place the patient's hand. This cut-out has a radius of 7.5cm and is placed 30cm from the top of the shield. The positioning of the cut-out accounts for the general heights of the bed in the lab, allowing for comfortable hand positioning for the patient and gives the operator enough access to the patient's arm as they require. The design can be seen in Figure 9. The material selection and manufacturing techniques of this shield are addressed later in the paper.

Figure 9: Image showing the shield with the hand-cut out.

Outer Frame

The outer frame of the shield holds the shield and connects it to the wheels, allowing for mobility of the design. The frame can be made of galvanized steel, which is strong, corrosion resistant and comparatively cheaper than other metals. The frame contains slider slots that hold the shield in position, as shown in Figure 10. The shield can be slid into the slot and locked into place, as shown in Figure 11, with two pin bar handles at the top of the shield. The slider slots make replacement of the shield easier and cost efficient, such that the outer frame does not need to be replaced, and only the inner shield would need to be replaced once it has worn out due to the radiation absorbed.

Figure 10: Image shows the outer frame with slots

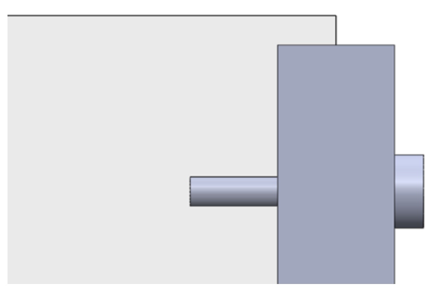


Figure 11: Image showing the locking pin at the top of the shield

The outer frame also contains a ledge, as shown in Figure 12, that is used as a base to place the hand plate (which is used to place the patient's hand during a procedure. This extension can be seen in the image below. The extension has a width of 3cm and a length of 30cm across the shield, towards the hand cutout. The length of the ledge was chosen to provide stability to the hand plate that will be placed on top of the ledge.

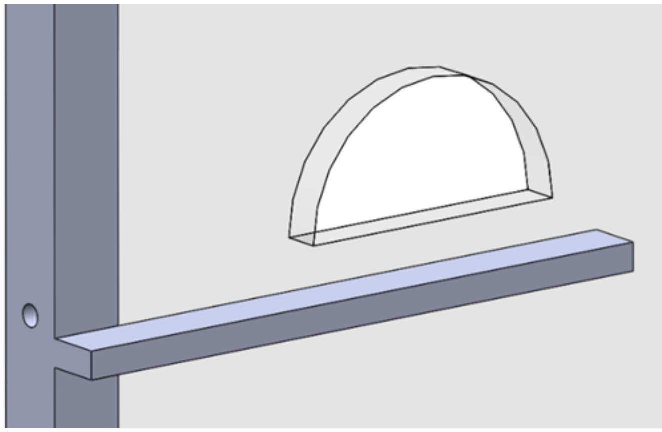


Figure 12: Image showing the ledge attached to the outer frame that supports the hand plate

Connected to the outer frame is a handle that is used for controlling the movement of the shield. This handle can be seen in Figure 13. The handle is screwed into the outer frame and can be made from the same material as the outer frame.

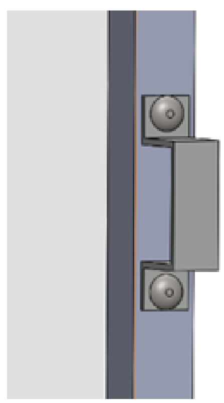


Figure 13: The image shows the handle connected to the outer frame.

Hand Plate

The Hand plate, as seen in Figure 14 is used to support the arm of the patient while the operator carries out the procedure. The plate is attached to the outer frame and is connected to it using a universal L joint that brings the plate down, as shown in Figure 15, and then rotates the plate to lay it flat on the ledge as shown in Figure 16.

The plate is 30cm wide by 40cm long. It is 1.5cm thick and provides a stable base with enough area for the operator to appropriately place and move the patient's hand as required during the procedure. The hand plate can also be made from galvanized steel. The rotation of the plate allows the plate to be put away after the procedure is over.

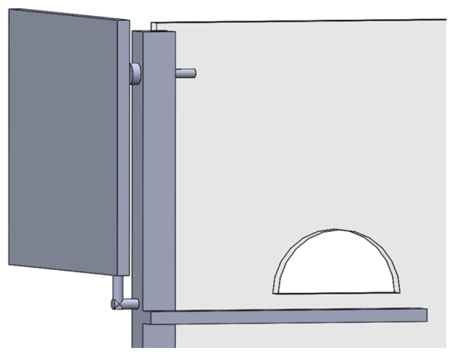


Figure 14: The image above shows the hand plate in the initial position when it is not in use

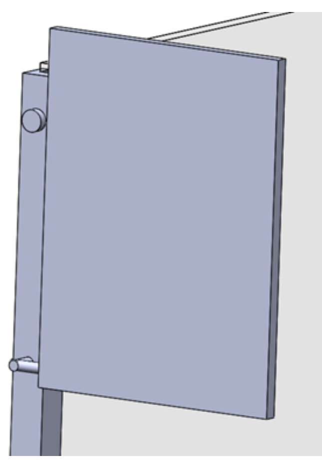


Figure 15: The image shows the hand plate in an intermediate position.

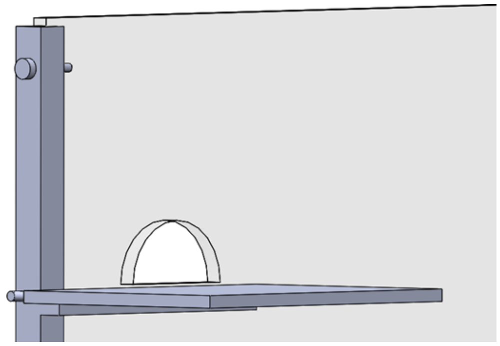


Figure 16: The image shows the hand plate in the final position, where it is ready to use.

Wheels

The shield is made mobile through a system of 4 wheels, which all move in one direction. These wheels are like those that can be found on pieces of furniture and can be seen in Figure 17. The wheels are connected to the outer frame using connecting rods that elevate the shield 40cm from the ground. The connecting rod then splits into two ways, allowing for two wheels on each side of the shield. A total of four wheels provides stable, steady, and controlled movement of the shield.

Each wheel has a brake that stops the wheel from rotating. These brakes make the shield stationary during a procedure, reducing the risk of any accidents during the procedure.

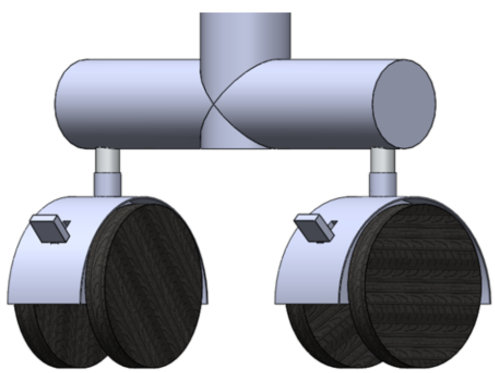


Figure 17: Image shows the wheels designed for the shield.

7 Shield Material Analysis

As stated above, radiation in catheterization lab procedures predominantly involves the use of X-rays, which have wavelengths in the range of 0.01 nm up to 10 nm [3]. This corresponds to a photon energy range of 100 keV down to 100 eV [3].

As of the date of publishing, the Grady Hospital staff primarily use leaded material as shielding, due to its superior ability to shield X-rays in comparison with other materials. With a high Z number, high density, and low cost, lead has been a cheap and efficient method for preventing radiation spread for decades. However, leaded materials have significant drawbacks, such as high toxicity, heavy nature, poor flexibility and low chemical stability. More importantly, they exhibit a blind absorption zone for X-rays in the 70 − 90 keV range [10]. This relationship is outlined in Figure 18.

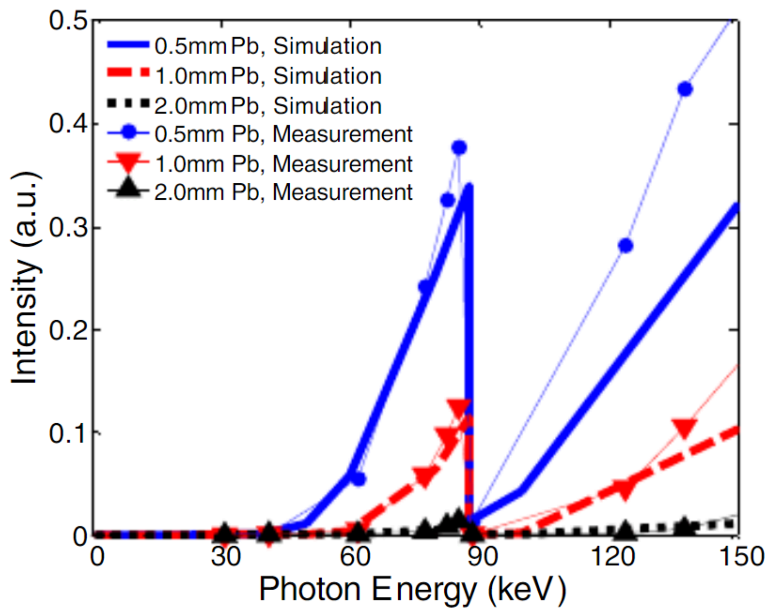


Figure 18: X-ray transmission intensity between simulated and measurement results across 0-150keV energy transmissions. Three Pb sheets with varying thicknesses are studied. [10]

As shown in Figure 18, the absorbance of lead (Pb) dips between 50-90 keV, with a dangerous blind absorption zone between 70-90 keV. While these effects can be halved by doubling the thickness of lead sheets, the toxicity levels operators are exposed to will also increase [10]. In practice, a 0.5mm Pb sheet is deemed to provide sufficient shielding, as it is the most cost effective solution. Figure 19 highlights the transmittance and absorbance rates for this sheet.

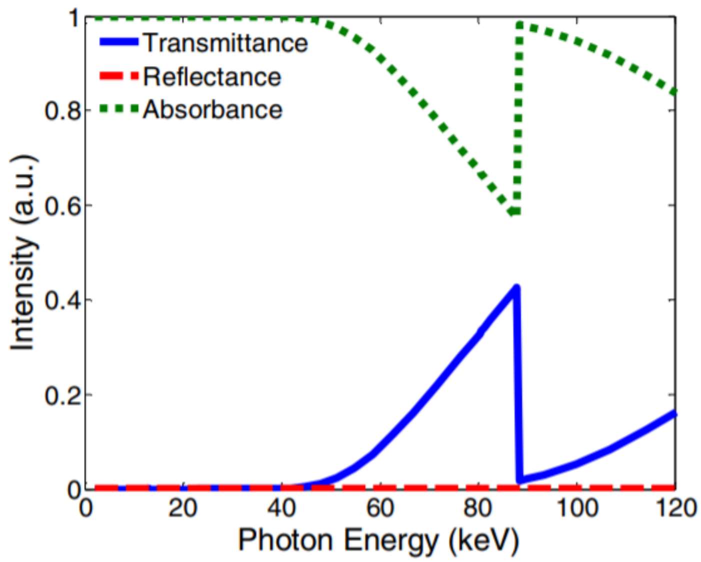


Figure 19: Transmission, reflection and absorption spectra versus energy of a 0.5mm Pb sheet. [10]

While 0.5mm Pb sheets are the norm in most medical procedures, there is a clear blind absorption zone, especially for advanced procedures requiring X-Rays of higher energies. In this zone, the Pb sheet only absorbs approximately 60% of high-energy radiation, as illustrated in Figure 19.

Alternatives Materials Discussion

When considering an alternative shield material to use, three factors must be taken into consideration (in order of priority):

1. Efficiency. The new material must have high radiation attenuation i.e. it should absorb at least 60% of all radiation between 50-90 keV. Fulfilling this criterion will ensure the new material is more efficient than a Pb sheet.

2. Cost. While this material is being suggested within the context of its application in the Grady Hospital cath lab, it has potential applications in cath labs around the world. Considering that hospital equipment funding is scarce in many countries, the cost of the new shield material should be similar to the standard Pb shield. Upon consultation with the doctors, an arbitrary 20% extra buffer cost was set as the cost limit of this study i.e. the new material shield should cost less than 120% the cost of a standard Pb shield.

3. Transparency. As the shield will be placed between operators and the patient, the operators must be able to see through the shield to the patient. The material should achieve a similar transparency level to the standard Pb shield i.e. the shield should at least be translucent.

The two metals identified as being satisfactory alternatives for Pb are Tungsten (W) and Bismuth (Bi). The superior workability and flexibility of W alloys means they can be configured in various ways to suit this growing and increasingly versatile demand. Anti-scatter grids and collimators are among the most typical components fabricated from W alloys for use in medical imaging. W has a high Z number (73) and is approximately 1.7 times more dense than Pb, allowing it to provide the same photon attenuation and radiation shielding as Pb with less material. Figure 20 shows its effectiveness in reducing radiation transmission, especially between the blind absorption zone of 70-90 keV. However, due to its very expensive comparative cost [11], a more cost-effective alternative would involve compounding with another element to form a tungsten alloy. The most widely used alternative compound is a W/Bi alloy.

Bismuth (Bi, Z = 83) is one of the less toxic heavy metals. Recently bismuth oxide (Bi_2O_3) is used in the preparation of different glass systems that are used for radiation shielding [12]. Despite this, Bismuth alone is similar to lead in its radiation shielding properties, and does not account for the blind absorption zone issue (Figure 20).

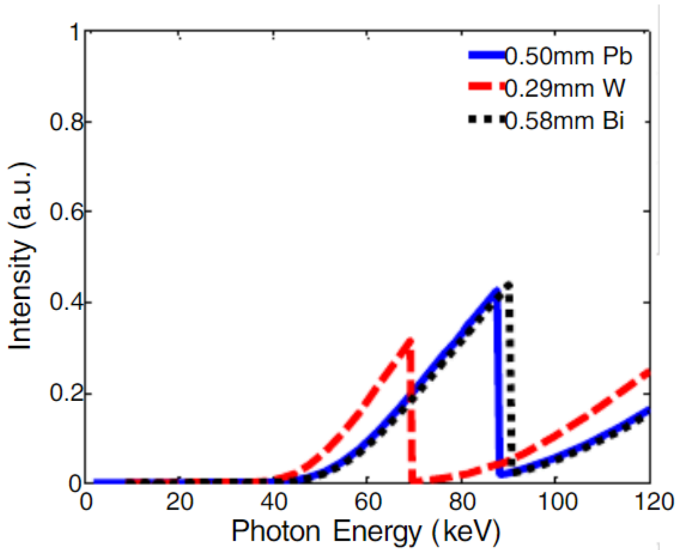


Figure 20: Transmission spectra of W, Bi, and 0.50mm Pb at the same weight. [10]

As a result, a W/Bi alloy is recommended. A W/Bi double-layer sheet is shown to be far more effective at preventing radiation transmission, especially in the blind absorption zone.

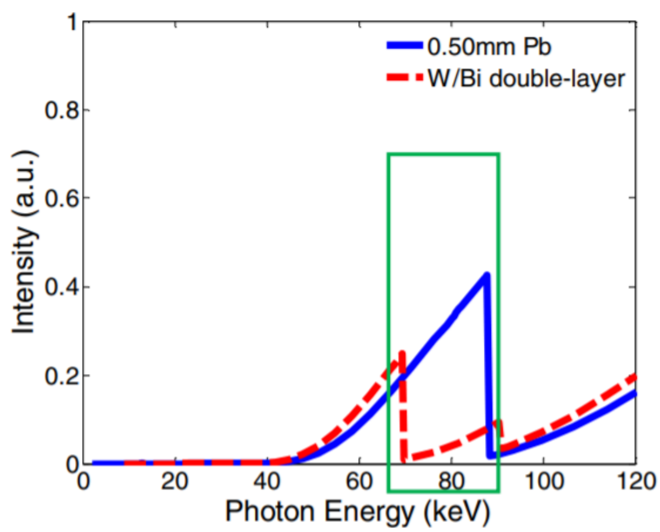
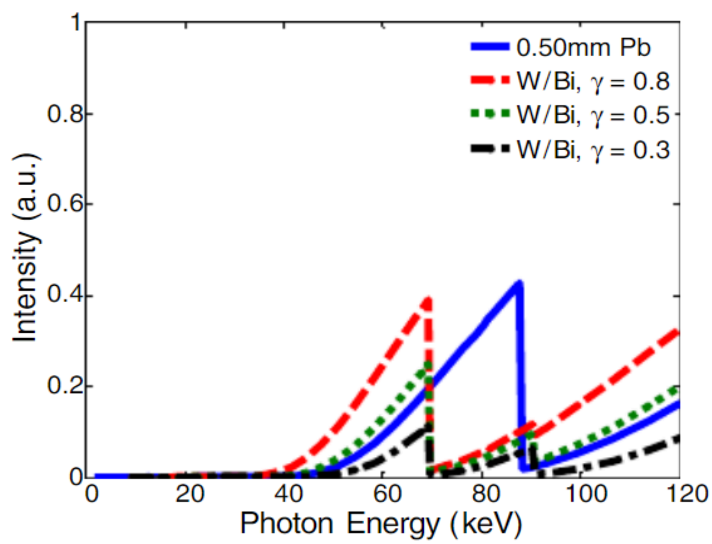


Figure 21: Transmission spectra versus energy of 0.5mm Pb sheet and double-layer W/Bi sheet at same weight, with W and Bi thickness of 0.29mm and 0.58mm respectively. [10]

As displayed in Figure 21, a double-layered sheet with one W layer and one Bi layer reduces the transmission in the blind absorption by at least a factor of 4. All other variables, such as weight of sheet, were kept controlled. This highlights the great potential of W/Bi sheets as alternative non-toxic shielding materials that further prevent radiation exposure. During another comparison, a 0.17 mm W/Bi double-layer sheet proved to provide the same protection properties as the standard 0.50 mm Pb and was 36% lighter [10].

Mixing and Arrangement of W/Bi

With the optimal material chosen to be a mixture of tungsten (W) and bismuth (Bi), the mixing properties and ratios can be explored and observed.



The double-layer W/Bi sheet is observed in different thickness ratios at γ= 0.8, 0.5, and 0.3. The thickness of W is fixed at 0.20 mm. The thicknesses of Bi are 0.05 mm, 0.20 mm, and 0.47 mm for the thickness ratio of 0.8, 0.5, and 0.3, respectively.

Figure 22: Transmission spectra versus energy of double-layer W/Bi sheet with varying thickness ratios. [10]

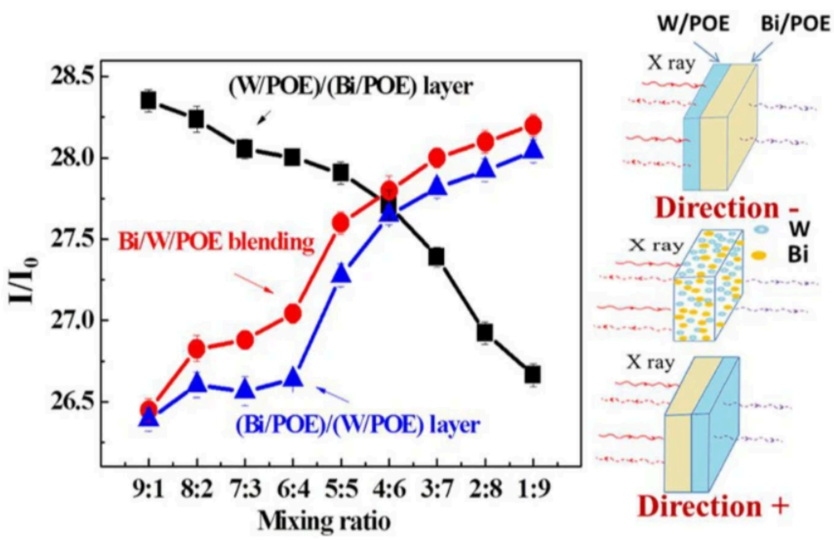


Figure 23: Dose ratio of X-ray passed through the blending and layered composites, with different layer thickness ratios. [10]

With an increase in the Bi content, the photon transmittance decreased sharply, as displayed in Figure 22. In other words, the shielding efficiency was significantly enhanced. The atomic number of Bi is higher than that of W. Furthermore, the Bi atom is larger than the W atom and hence is more conducive for inducing the photoelectric effect and dissipating the energy of photons. As a result, more Bi-based composites exhibit excellent shielding ability for X-rays. For maximum protection, a thickness ratio of W/Bi of 0.3 is suggested.

An additional consideration is whether a layering method is the most optimal layout of W/Bi atoms such that radiation transmittance is reduced. Figure 23 suggests a more superior blended approach, where the atoms are completely mixed together.

Transparency

One key criterion the W/Bi material must pass is the transparency test. Standard leaded glass composed of 38% Pb has a light transmission rate of 86-88% [13]. Furthermore, the leaded acrylic currently used in Grady Hospital has a refractive index of 1.55 [14]. The real refractive index of a material *n* is related to the transmittance T of light from air through that material by the Fresnel equation [15]:

$$T = 1 - \left(\frac{n-1}{n+1}\right)^2$$

Equation 1: Fresnel's equation relating transmittance of light from air through a material with real refractive index n (with the assumption that the light rays are incident normal to the plane of the surface). [15]

Using Equation 1, leaded glass/acrylic has a transmittance of 86-95% with a refractive index of 1.6 to 2.1. Raw Pb has a complex refractive index of 1.7860 + 3.3620i [16]. To increase transmittance, the aim is to find a material with a real refractive index as close to 1 as possible, and a complex index as close to 0 as possible.

Raw W has a real refractive index of approximately between 1.8 to 2.4 and an imaginary index of 2.4 to 2.8 at the same wavelength [17]. Raw Bi has a refractive index of 1.9753 + 2.7952i [18]. By utilizing the real parts of the refractive indices of W and Bi, a combined refractive index of a W/Bi alloy will be the RMS value of both real refractive indices R_{RMS} [19].

$$R_{RMS} = \sqrt{\frac{1}{2}\left(2.1^2 + 1.9753^2\right)} = 2.039$$

Equation 2: Theoretical combined refractive index of W/Bi alloy sheet. [19]

This real refractive index of the alloy is 2.039 is already quite close to the refractive index of Pb. Placing it inside a glass shell with a refractive index of 1.5, the refractive index of the entire alloy-glass compound is:

$$R_{RMS} = \sqrt{\frac{1}{2}\left(2.039^2 + 1.5^2\right)} = 1.790$$

Equation 3: Theoretical combined refractive index of alloy-glass compound. [19]

This refractive index of 1.790 is very close to the refractive indices of leaded glass/acrylic. Using Equation 1, this alloy-glass compound is theoretically less than 13% less transparent than the leaded materials.

Financial Considerations

Now, the W/Bi alloy is the most effective solution at radiation prevention, however both heavy metals are significantly more expensive than the classical 0.50mm Pb shield. While it is difficult to gauge a price without specifically acquiring a quote from any manufacturing company, the approximate costs are outlined in Table 1. The dimensions of the proposed shield with a W/Bi alloy is 132 x 102 x 2 cm, which has the same thickness of a standard lead shield. However, these shields have an acrylic casing with a radiation-protective material sheet. Since the cost analysis only considers the raw material costs, the cost of a standard lead sheet of dimensions 132 x 102 x 0.050 cm is compared to the cost of a W/Bi sheet of dimensions 132 x 102 x 0.017 cm (sheets offering the same protection).

Table 1: Approximate costs of each raw material as of date of publishing.

Material	Cost per lb (US$)	Density (lb/cm^3)	Cost per cm^3 (US$)	Total Cost (US$)
Pure Tungsten (W)	3.2500 [11]	0.04254922 [20]	0.138284965	-
Pure Bismuth (Bi)	3.9250 [21]	0.0214884567 [22]	0.084342193	-
W/Bi with $\gamma = 0.3$	3.7225	0.02523577319	0.0939401657	21.5018
Pure Lead (Pb)	1.1000 [23]	0.025044513 [24]	0.0275489643	18.5460

The equation used to calculate the density of the alloy is:

$$\frac{1}{D_{alloy}} = MF_1 \cdot \frac{1}{D_1} + MF_2 \cdot \frac{1}{D_2}$$

Equation 4: Calculating average density of alloy from constituent components.

where D_{alloy} is the density being calculated, MF_i is the fraction of the mass occupied by each metal, and D_i is the density of each metal.

To calculate the price of the alloy, a distributive cost was used based on the suggested mixing ratio. Since the alloy composition is 30% W and 70% Bi, the alloy price is estimated as follows:

$$P_{alloy} = 0.3P_W + 0.7P_{Bi}$$

Equation 5: Calculating rough estimate of price of raw materials for alloy production.

where P_{alloy}, P_W, P_{Bi} are the prices for the alloy, for raw W, and for raw Bi, respectively.

From using Equations 4 and 5 in Table 1, it can be deduced that the proposed W/Bi shield costs $2.96 more than the pure lead shield alternative per shield, a 15.9% cost increase which is below the 20% buffer goal. Hence, from a financial perspective, using the ballpark figures provided, the W/Bi material shield is a cost-effective alternative. It must be noted, however, that these costs are approximate figures, and do not account for additional manufacturing costs stated by the company quotation.

8 Alloy Manufacturing Processes

While it is difficult to find any specific manufacturing information without selecting a production company and formally requesting a quotation, the two general alloy production methods can be studied: die casting and powder metallurgy.

Die casting is the most common alloy development method. The concept behind this involves the melting of metals into liquid form, at which point it is “forced into a steel mold under high pressure into a mold cavity. The steel molds, known as dies, are fabricated to produce castings with intricate shapes”. This involves a 5-step process: clamping of the dies, injection of molten metal into dies, cooling of the metal, ejection of the casting, and trimming of excess metal [25].

Powder metallurgy, on the other hand, is a newer method that involves sintering. While melting is the complete transition of a solid to a liquid state, sintering is a heat treatment process where loose material is subjected to high temperature and pressure in order to compact it into a solid piece [26]. This is similar to when ice cubes adhere together in a glass of water due to the temperature difference between the ice and the water, or when snow is pushed together to form a compact snowball. Just as a material has a melting point, it will also have a desirable sintering point, at which the heat and pressure are enough to reduce the porous spaces between the material's particles and squeeze loose material together into a solid lump [26]. Some plants may also utilize a pressure assisted full density processing technique, and further research can explore the benefits and drawbacks of each technique [27].

Table 2: Comparison of powder metallurgy and die casting [28].

HORIZON TECHNOLOGY	QUALITY	MATERIAL IMPLICATIONS	MECHANICAL PROPERTIES	COST
PM	*CONSISTENT HIGH QUALITY*	*GREATER FLEXIBILITY (IN MATERIAL USAGE)*	*HIGH VARIABILITY (MORE POSSIBILITIES)*	*LESS WASTE/ MACHINING (LOWER COST ON AVG.)*
DIE CASTING	*INCONSISTENT HIGH QUALITY*	*NONFERROUS METALS (LOW MELTING POINT)*	*LIMITED POSSIBILITIES (DUE TO MATERIALS)*	*MORE WASTE/ MACHINING (HIGHER COST ON AVG.)*

When comparing the two methods, powder metallurgy/sintering provides far greater benefits, in especially with costs, as exhibited in Table 2. With regards to the proposed shield W/Bi alloy, the melting points and sintering points of both elements must be considered. While bismuth has a low melting and sintering point, tungsten's melting and sintering points are 3420℃ and 1400℃ respectively [29]. It's clear that the sintering process is far more cost-effective and practical than the die casting alternative.

The consistency of product created from the sintering process is also known to be far better [28]. This is because the precision dies, punches, and core rods have closer tolerances than die cast parts. Furthermore, the compacting process in powder metallurgy ensures that a uniform weight of powder is spread out into the die and compacted to the same density. In casting, the cooling rate also varies across different sections of the part. Because of these different cooling rates, the microstructure and resulting properties may vary across the part.

Another advantage of powder metal is microstructural control through cooling [28]. In casting this depends on cooling rate, which varies based on surface area and volume. The composition is the same throughout the part, but because of the different cooling rates, the microstructure and resulting properties can vary. When sintering, since the metal is heated to a lower point, the cooling rate is far less, offering more control and consistency during the cooling process.

The main disadvantage of sintering is that large quantities of material are required to justify the higher initial tooling costs. Assuming that the scope of manufacturing for this shield is large i.e. a lot of shields are in demand, powder metallurgy is far more consistent and easier to carry out, especially in the context of mass production. However, as die casting is widely seen as the conventional method, it should also be considered when conducting a cost-benefit analysis of manufacturing choices. Overall, however, both processes will allow fabrication of a shield with good consistency and quality, both in the material properties and mechanical properties.

Manufacturing Multiple Sheets for One Shield

While the original manufacturing process involved molding one sheet of W/Bi alloy to a much thicker acrylic material, an alternative involves inserting two or more sheets into the same acrylic material, resulting in an overall increase in radiation attenuation. However, the biggest conflicting barrier to that alternative is transparency. The more sheets that are inserted into the shield, the harder it becomes for light to travel through all sheets. Thus, the one-sheet molding with acrylic is preferred over multiple-sheet molding.

9 Placement of Design in Cath. Lab

The general position of the shield in the lab would be between the operator and the patient, such that it does not interfere with the motion of the C-Arm. This can be seen in Figure 24 below. The distance between the shield and the patient may vary depending on the length of the catheter used, and the length of the patient's hand. Placing the patient's hand through the semi-circle cut out and onto the table that the operator would be working on creates a sizable distance between the operator and patient, about 25cm, and it is in this gap that the shield should be placed. Figure 25 refers to a possible orientation of the lab with the shield.

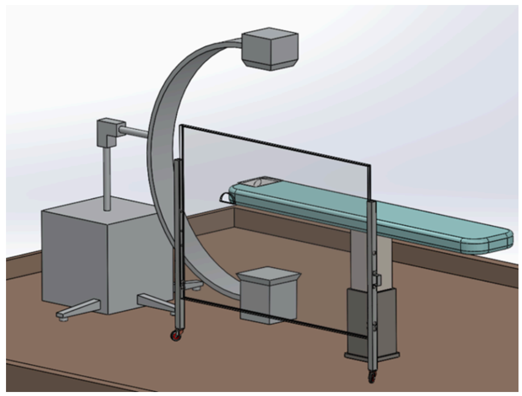


Figure 24: Showing the shield in the cath lab environment

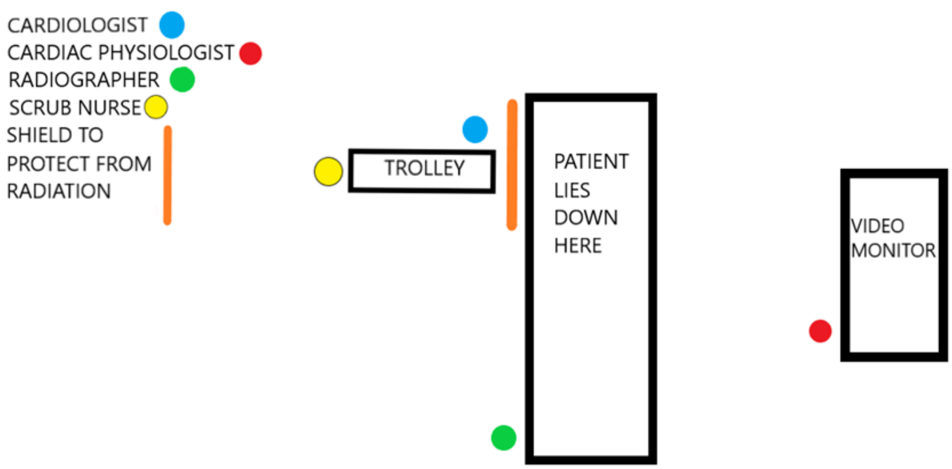


Figure 25: Showing a possible set up of the lab with the shield

10 Further Research

This suggested model has a lot of scope for further research and personalisation in different labs. One such area of further research involves a study of the efficiency of this unconventional tungsten-bismuth alloy. Combining the results of this study with a deeper look into the manufacturability and costs (both monetary and environmental) from this material choice could be a fruitful subject of a further report.

Another consideration to include is that each lab around the world is different in size and its overall operation. Further reports can branch into more details regarding specific recommendations made for specific labs. As an example, a smaller lab with fewer resources may consider the effects of reducing the shield size from a full-body shield to one that simply protects from the face to the middle of the torso. The size of the wrist hole on the proposed design can also be studied further to maximize its ergonomic design and make the procedure more comfortable for the patient.

11 Conclusion

This report establishes potential for another floor-mounted design with a more effective shielding material. This proposed design support system fulfills all the criteria for a good shielding structure: it is maneuverable yet stable (even when moving), has minimal stress at key/critical points along the structure, and is cost-effective. The manufacturability of this support structure is very feasible, considering it is quite similar to existing shield support structures.

The novel W/Bi alloy has great potential for revolutionizing non-lead shielding materials, and can help move hospitals away from toxic lead-based shields. While lead sheets allow up to 40% of high-energy radiation to pass through, the alloy reduces this figure to approximately 10%. Furthermore, the W/Bi alloy is lighter and less toxic than lead-based materials. Theoretically, this alloy can be manufactured in the same way as leaded acrylic, in that an alloy sheet can be made using sintering/molding.

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