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Reducing Occupational Radiation Exposure in Cardiac Catheterisation Laboratories: Dose Rate Predictions and Feedback Strategies

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Preface and Acknowledgements

With this Master's thesis, my eight years studying at the Technical University of Delft comes to an end. Throughout this journey, I have gained invaluable knowledge about the field, personal growth, and my future aspirations. Outside my studies, I explored various learning opportunities beyond the standard curriculum; participating in committees, serving on the board of the study association Variscopic for a year, and working at the start-up Corsano Health for two years. At Variscopic, I investigated external opportunities for technical medical professionals beyond hospitals. At Corsano, I was responsible for building, as so often discussed, the bridge between new technology and healthcare facilities.

While seeking my graduation project, I looked for a creative endeavour focused on implementing new techniques in healthcare. During my internship at Philips, I spoke with Benno about his involvement in inventing the CD and holding the most patents within Philips. He introduced me to this project, and I knew I had to get involved. Coincidentally, the director of TM, John, was the other person responsible for the project, creating a dream team!

I would like to express my gratitude to John van den Dobbelsteen, Maarten van der Elst, and Benno Hendriks for our weekly meetings, guidance, and positive feedback, which kept me motivated and engaged. Additionally, I thank Teddy Vijfvinkel for the daily support and camaraderie during the graduation process. Also, I appreciate Joost Geldhof for his (sometimes overly) critical perspective on the project's measurements and underlying physics. Furthermore, I want to thank Jan Constandse for making it possible for me to consistently observe and participate in cardiology and cathlab sessions, as well as for always being open to discussions about new techniques in healthcare.
Last but not least, I would also thank all my family and friends for always supporting me and making my time as a student unforgettable.

Thijs van Deudekom
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Summary

Introduction - The increasing use of cardiac catheterisation procedures has raised concerns about occupational radiation exposure and its associated health risks for clinicians. Radiation exposure can lead to deterministic and stochastic effects, including cataract and various cancers. To minimise these risks, the ALARA (As Low As Reasonably Achievable) principle must be followed in the clinical setting by applying the available measures. Radiation protection consists of passive and active measures. Passive protection includes architectural shielding, stationary shielding, and personal protective equipment, while active protection focuses on minimising radiation during interventions, employing adjustable lead screens, modifying imaging techniques and provide feedback to improve the usage of these measures. However, current methods for measuring and providing feedback on radiation exposure are insufficient.

The primary goal of this research is to find a comprehensive and improved approach to guidance and implementation of protective measures, to ensure the safety and well-being of healthcare workers who face radiation exposure in their daily practice. An integral component of achieving this goal is to create a model that calculates radiation exposure for clinicians in the cathlab with the use of a lead screen. This research aims to determine the feasibility of using dose rate data from measurements without a lead screen to estimate the dose rate in an environment where a lead screen is employed. Moreover, potential methods for communicating dose rate data to clinicians during a procedure will be explored, aiming to increase their awareness of radiation exposure and encourage the adoption of appropriate protective measures without distracting them from the procedure itself.

Method - Data collection is necessary to construct a model that can predict the radiation scattering. Measurements in the catheterisation laboratory were performed by placing Philips DoseAware Detectors (PDDs) at various locations and heights. Combinations of fluoroscopy or acquisition mode, anteroposterior (AP) view or a 40° tilted view of the C-arm, and the presence or absence of a lead screen, resulted in eight different setups, with each 168 measurements.

In the programming process careful consideration has been given to the ease of refining and improving the model afterwards. Three potential source options for the radiation were considered: the centre of the phantom, a point where 50% of the scattering has occurred, and a 3D representation of the entire phantom. The modelled lead screen together with the source was used to create an attenuation grid, which will be used for the estimation of the effect of the lead screen.

The adequacy of the estimated dose rates with the lead screen was evaluated using boxplots and counting the number of correctly estimated points. Then, the data was interpolated using Kriging. The interpolated data was visualised, and the radiation doses for the assistant and cardiologist were calculated at the chest and head levels.

The exposure calculation was performed for three lead screen positions and a scenario without the lead screen. The placements considered were close to the clinician, close to the phantom, and at the edge of the phantom.

To explore radiation feedback preferences, a literature review and a questionnaire for interventional cardiologists were conducted.

Results - Measurements were taken for eight different setups, each with 168 measurements, including the combinations of fluoroscopy or acquisition mode, anteroposterior (AP) view or a 40° tilted view of the C-arm, and the presence or absence of a lead screen. The interpolated data revealed that the dose rate is higher when the

acquisition mode is used, and radiation levels are higher when the C-arm is rotated. Three different source types were incorporated into the measurements, and the accuracy of the estimations was evaluated based on whether they were within a deviation of 0.1 mSv/h from the actual measurements. The 3D source was found to be the most accurate representation of the source in the model. Visualisation of inaccurately estimated values showed that the model overestimated the amount of radiation blocked in certain cases. The radiation exposure for clinicians increased as the lead shield was positioned closer to the radiation source.

A questionnaire was conducted with five interventional cardiologists to investigate their radiation safety practices. The results indicated that radiation safety is deemed important, with an average score of 8/10. The lead screen is an essential shielding component, but its placement varies, and there is uncertainty regarding its optimal positioning. Monthly reports on total radiation dose exposure were provided. The clinicians hardly paid attention to this information, as they believed that any potential harm had already occurred.

The highest-rated techniques were advice on optimal lead screen position (displayed on the lead screen) and a visualisation using augmented reality that displays the scatter pattern on the monitor.

Discussion and Conclusion - This study addresses radiation safety in interventional cardiology by exploring protective measures. A preliminary model was developed to predict radiation exposure based on the location of the lead screen enabling the computation of the radiation dose received by clinicians during a procedure. This dose rate model helps to visualise the impact of lead screen positioning on radiation exposure, which can aid in real-time decision-making during procedures. The model also revealed that placing the lead screen closer to the clinician, rather than closer to the source, could potentially enhance radiation attenuation by a factor of 6.2. This results in a possible dose reduction up to 32.5 times.

The most preferred option by the interventional cardiologists was to display the suggestion of the optimal position of the lead screen directly on the shield. A potential addition to the feedback system could be an augmented reality (AR) visualisation of the radiation effect on the monitor, clearly showing safe areas for personnel. The precise feedback mechanism should be piloted and refined to ensure seamless integration into clinical practice without distracting the clinician from the procedure itself.

Understanding the limitations of the measurements and the model is crucial for optimising its application in practice and the improve the reliability. The accuracy of measurements obtained with the DoseAware badges, while sufficient for this project, could be improved by using more accurate instruments. The phantom used in the study does not accurately represent real patients, and future research should involve patient-specific inputs and more realistic phantoms. One of the key future objectives include collecting more data in different settings and positions of the C-arm, as well as investigating different positions and orientations of the ceiling-mounted lead screen.

The model itself has limitations in its representation of the scattering source and interpolation methods. To improve the model, researchers should account for other sources of scatter, and assess alternative interpolation techniques using more powerful computing resources. Moreover, to calculate the received radiation dose, the model should consider the entire body, accounting for the protection provided by a lead apron and the concept of effective radiation dose.

Accomplishing these objectives will allow the model to play an important role in enhancing cathlab radiation safety, benefiting the health and safety of clinicians.

Contents

Introduction

Quality assurance plays an increasing role in human medicine. In radiology, it not only involves image quality and reliability of diagnosis but also radiation safety and protection of patients and medical professionals, which is often neglected in the daily routine [1] [2]. In recent decades catheter procedures have changed the way patients are diagnosed and treated at the cardiology department [3]. Diagnostic and interventional cases require the use of X-ray images to enable the doctor to visualise the anatomical location and proper use of interventional equipment. These procedures are performed in a catheterisation laboratory (cathlab), using a C-arm as showed in Figure 1.

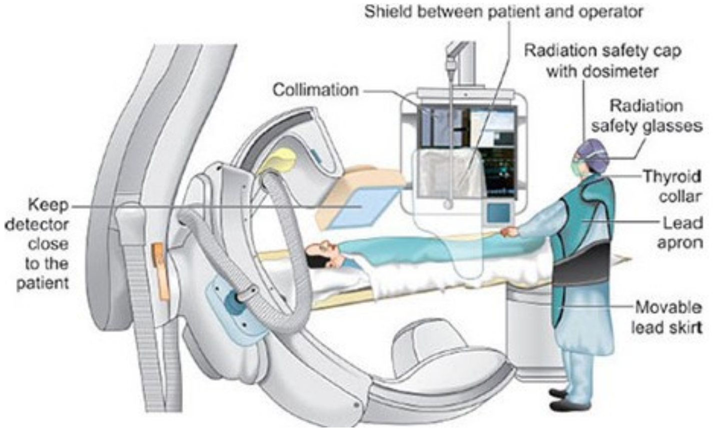

Figure 1: Catheterisation Laboratory with possible protective measure

Ionising radiation exposure poses an inherent risk of damaging tissue at the molecular level and can cause tissue responses in both the patient and exposed personnel [4]. As the medical staff receives radiation with every procedure, occupational radiation exposure is a major concern in cardiac catheterisation laboratories. In the study of Vano et al. they monitored the radiation exposure of medical staff in the interventional and cardiac radiology. The medical staff was monitored using nine dosimeters, which resulted in a distribution pattern of the dose exposure, as shown in Figure 2 [5]. As advancements continue to broaden the possibilities within the field of medical imaging, clinicians will increasingly leverage these new opportunities, resulting in an increasing radiation dose. This raises the question of whether the additional radiation required outweighs the benefit of imaging and if it can be reduced.

Effects of Radiation Exposure

Radiation has a linear, dose-dependent risk profile for which there is no minimum safety threshold. Ionising radiation can have either deterministic or stochastic adverse effects on human tissue.

Deterministic effects occur when the dose exceeds a specific threshold. The severity of deterministic effects commonly increases with dose, as more cells are damaged. Examples include infertility, skin erythema and scaling, and cataract [6]. For instance, the lens of the eye is prone to receive high radiation doses. Consequently, an increased prevalence of cataract and lens opacity has been observed among interventional radiologists and cardiologists [7]. Compared with those not exposed to fluoroscopy, interventional cardiologists have a threefold greater occurrence of posterior subcapsular lens opacity [8].

Stochastic effects are those for which the probability of an effect, rather than its severity, depends on the dose of radiation received. It has a long latency period and involves no threshold dose under which genetic material remains completely intact. Typically, these adverse effects are cancer of the skin, thyroid, nervous system, and gastrointestinal tract [9]. Cases of brain tumours disproportionately often on the left side have also been reported in doctors performing interventional procedures [10]. Radiation exposure on the left side of the head is known to be twice as high as on the right, which can also be seen in

Figure 2. Also, the hand receives a significant amount of radiation (45-1500 μSv per procedure) during the procedures, as it is not shielded and is close to the radiation source. However, this level of exposure is unlikely to cause adverse health effects [11].

In order to minimise the risk of the clinician experiencing adverse effects, the ALARA (as low as reasonably achievable) principle will have to be adhered in order to ensure a safe working environment.

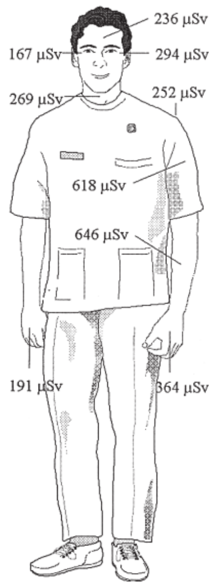

Figure 2: Graphic presentation of the mean values of doses per procedure found at the locations monitored for an interventional cardiologist [5]

Potential Radiation-reducing Measures

Radiation protection consists of two parts: an active and a passive component. The passive component consists of measures that cannot be influenced during the intervention, such as (personal) protective equipment and secure devices. The active component focuses on limiting radiation exposure during interventions, including using adjustable lead screens and adjusting imaging techniques.

Passive Protection

Passive protection strategies primarily consist of architectural and stationary shielding as well as personal protective equipment. The personal protection includes wearable aprons, thyroid collar, eyewear, gloves, and caps. While the aprons and thyroid collar are generally accepted and worn, only 30% of the interventional radiologists have been reported to use the lead glasses [12]. This is concerning, because eye problems are common negative consequences of radiation for the operator and lead glasses can result in a radiation reduction of 35% to 90% [13, 14]. The use of protective gloves or caps are even less accepted. Lead-containing gloves exist, but they are large and cannot be used when dexterity is required. Lead-based (or lead-free) radiation-absorbing latex gloves implemented in some centres help to overcome these problems. According to Kim et al., these gloves can protect the hand by 20 to 50% but are still not widely used [15]. Lastly, the lead cap is also not commonly employed. Compared to ceiling-mounted lead shields, lead caps that cover the sides and bottom of the face have been shown to reduce radiation exposure to the head [16]. However, a lead cap weighs about 1,140g, which can further contribute to discomfort orthopaedic injuries in operators [17]. Lead-free alternatives are now available, such as surgical caps containing bismuth and barium, which weigh only 53g. However, a recent study has shown that radiation scatter mainly comes from below the doctor's head and that radio-absorbent surgical caps do not cover this area. The radiation dose to the brain has been shown to decrease by only 3.3% - an almost negligible amount [18].

In addition to shielding, development in imaging devices also provides a considerable reduction in radiation. Compared with traditional fluoroscopy, relatively new image noise reduction technology enables the radiation dose to be halved [19]. In conclusion, the lead apron and thyroid collar provide good protection, but the other personal protection equipment provides either insufficient protection or are too inconvenient for the clinician to wear. To ensure the shielding of the exposed body parts, active protection strategies will have to be applied.

Active Protection

Active protection strategies include routine and appropriate use of lead apparel, using techniques in reducing radiation use to the patient and thereby to the operator, beam angulation and position yourself the room. An important element is proper training of the staff, so that they know where potential improvements can be made [20].

There are several techniques that can be implemented during the procedure itself to reduce the radiation dose. For instance, restricting fluoroscopy time to the time the operator is looking at the monitor. Rather than continuing to use more fluoroscopy to study the coronary arteries, review the final image hold or use a fluoroscopy loop for dynamic processes. In a similar way, the use of high-dose modes, including boost mode, override mode or high-contrast mode, should be reduced to a minimum [21]. Modifying the frame rate of fluoroscopy can also help reduce radiation exposure but will lower the quality of the image. Typically, the frame rate is set at 15 frames per second, and it has been shown that reducing it to 7.5 frames per second leads to a significant reduction in radiation dose [21]. It has been shown that adjusting the technical settings of X-ray equipment and applying dose reduction protocols can reduce radiation exposure by 48% [22]. In addition, the radiation dose to the patient can be decreased by an optimal table positioning. Ideally, the patient should be placed further from the X-ray source and as close as possible to the image receiver. Higher table setup lowers the skin dose to the patient [23]. Tight placement of the collimator blades results in better image quality and reduces scatter radiation. Comparable outcomes can be obtained by using semi-transparent or wedge filters [24, 25]. Due to automatic dose controls, the X-ray tube output will increase with the patient thickness. Keeping the non-target anatomy and the operator's hands out of the field of view or primary X-ray beam is important [14]. Apart from the fact that the direct radiation dose is significantly higher than from scattering, the radiator output increases due to the automatic brightness control system. This causes an unnecessary increase in radiation for both the patient and the clinician [11]. It has been shown that the angle of the tube affects the radiation dose to patients and operators. The main cause for this, is that a larger angle means a larger trajectory through the body. With the same mechanism deployed by the automatic dose controls mentioned before, this results in a higher dose with higher tube angles [26]. This higher dose with other tube is also the result of non-homogeneous scattering. Consequently, the dose to the clinician depends on where they are positioned and where the lead shields are located.

Alongside the shielding that is part of the passive protection, adjustable lead shields are regularly present as well. These are usually made of transparent lead-based plastic that can be easily adjusted during the procedure. Accurate placement of these is key to reducing operator exposure significantly. A gap in protection is often created by the patient's contour indentation. To optimise the protection in this area, the upper body screen should be placed close to the operator and far from the scattering source. The upper body screen should be moved regularly during the procedure when the table is moved, to ensure effective protection is maintained [18]. The amount of radiation exposure depends on the distance to the source, proportional to the inverse square of the distance to the X-ray source. Therefore, staff reduce their exposure by a factor of four by doubling their distance from the source [27]. In closing, there are numerous ways to improve radiation safety during surgery. However, it is difficult for clinicians to realise where and when they are receiving too much radiation and how they can deploy certain measures effectively.

Prediction models

There are several models that predict scatter patterns in the catheterisation laboratory, often employing Monte Carlo simulations [28]. Monte Carlo simulations are a computational method that utilizes random sampling to solve complex problems, often involving uncertainty or probabilistic phenomena. By simulating numerous scenarios and calculating outcomes, Monte Carlo simulations can provide valuable insights into the behaviour and distribution of variables in a given system. In studies conducted by Rodas et al. and J. Troville et al., researchers used predeveloped Monte Carlo systems to visualise scattering, experimenting with use of augmented reality and virtual reality (AR/VR) [29] [30].

However, none of the existing models consider the presence of a lead shield. Including the lead shield in such simulations could provide a more accurate representation of real-world conditions and potentially lead to more effective radiation protection strategies. Integrating this element into future models would be an important step forward in improving the safety and efficacy of radiation protection measures.

Concluding, it is vital to enhance radiation safety to protect medical professionals who are dedicated to providing the best possible patient care. The current method of measuring radiation exposure, which relies on a single stance-sensitive dosimeter, fails to provide an accurate representation of exposure levels. Additionally, the feedback mechanism for radiation data needs to be more efficient, effective, and accessible.

Goals and Objectives

The primary goal of this research is to find a comprehensive and improved approach to guidance and implementation of protective measures, to ensure the safety and well-being of healthcare workers who face radiation exposure in their daily practice.
A significant aspect of achieving this goal is to create a model that calculates radiation exposure for clinicians in the cathlab with the use of a lead screen. Since most radiation received by clinicians is caused by scattering, this is the aspect that needs to be accounted for [5]. This research aims to determine the feasibility of using dose rate data from measurements with and without a lead screen to estimate the dose rate in an environment where a lead screen is employed. Several sub-objectives will be investigated:

- Determine the most reliable representation of the source of the scattering.
- Explore the effect of the orientation of C-arm on the estimation of the radiation exposure

The model will be used to explore optimal lead screen positions, particularly whether it should be closer to the source or the clinician.

In addition to developing and evaluating such a model, possible improvements of the feedback will be discussed with interventional cardiologists. Potential methods for communicating dose rate data to clinicians during a procedure will be explored, aiming to increase their awareness of radiation exposure and encourage the adoption of appropriate protective measures without distracting them from the procedure itself.

By addressing these research objectives, this study aims to contribute to a better understanding of the factors affecting radiation dose rates in catheterisation laboratories and to develop improved radiation protection strategies. The outcomes of this study may lead to more accurate dose rate predictions, better usage of radiation protection, and ultimately minimise occupational dosage.

Method

In this study, a systematic methodology was followed to address the research objectives and optimise radiation safety in the catheterisation laboratory. Data was gathered for the development of the model, both from measurements with the lead screen and without the lead screen. This was performed using Philips DoseAware Detectors (PDDs) of Philips Health [31].

Philips DoseAware Detectors

PDDs are badges that can be worn by the staff and measures scatter radiation. Each PDD contains a silicon P-I-N diode, which is highly suitable as an X-ray detector due to its stability, sensitivity, and near-uniform response. These systems offer real-time feedback on radiation dose to users. A drawback of using such a diode system is its directionality, meaning it can only capture all the radiation when facing the radiation source directly. When the diode is positioned at an angle, it measures less radiation. This angular dependency is also outlined in Philips' instructions for use (IFU), which indicate that the PDD has an angular dependence of +/- 5% within +/- 5°, +/- 30% within +/- 50°, and +200%/-100% within +/- 90° [32]. A. Ehrenberger et al. conducted tests that supported these specifications, finding their test results with the badges available in the Reinier de Graaf Gasthuis to be consistent with Philips' PDD specifications [25].

The functional component of the PDD is a silicon P-I-N diode, which is composed of a lattice of atoms containing charge carriers—atoms with either space for an additional electron or extra electrons that can attach to other atoms. Silicon solid-state detectors have two layers of semiconductor material: the p-type, which has more available spaces (holes) than electrons, and the n-type, which has more electrons than available spaces. Electrons from the n-type migrate across the junction between the layers to fill the holes in the p-type, creating a depletion zone. This zone serves as the detector's detection area and operates similarly to an ion chamber, although with a more compact size and generating a smaller voltage. Radiation interacts with atoms in this zone, causing them to re-ionise and produce an electronic pulse that is subsequently measured. The detector's small size lends it real-time functionality because ion pairs can be collected rapidly [33] [34].

Figure 3: Measurement set-up for preliminary tests. On the left is the RaySafe X2 dosimeter. On the right are the Philips DoseAware Dosimeters

Preliminary tests

Before gathering the actual data, a preliminary test was conducted to evaluate the data return process and identify any unforeseen issues to address during the study. Badge measurements were compared with those of the Raysafe X2 dosimeter, which serves as the gold standard for radiation measurement [35]. Although the Raysafe is also a directional detector, it detects some radiation from all directions, with varying intensity depending on its angle relative to the source. The eight badges and the Raysafe were affixed to the side of a box facing the phantom, as the phantom was considered the scattering source (Figure 3). Five measurements were taken at a 50 cm distance from the phantom's centre to test precision and accuracy at a consistent dose rate. Nearly all badges demonstrated deviations within 10%, with the exception of the yellow badge, which had an average deviation of 60% (Figure 4). The precision was high, as the five measurements exhibited deviations within 2% of each other.

Subsequently, eight measurements were taken at distances ranging from 30 cm to 100 cm to determine whether deviations varied based on the received dose rate. A slight increase in deviation and a corresponding decrease in accuracy were observed with higher dose rates. The yellow badge, again, exhibited deviating measurements. However, after testing the yellow badge in other measurements, no further deviations were detected. Consequently, it was decided to include this dosimeter in the subsequent measurement setup, as the observed deviations were not replicated in other tests.

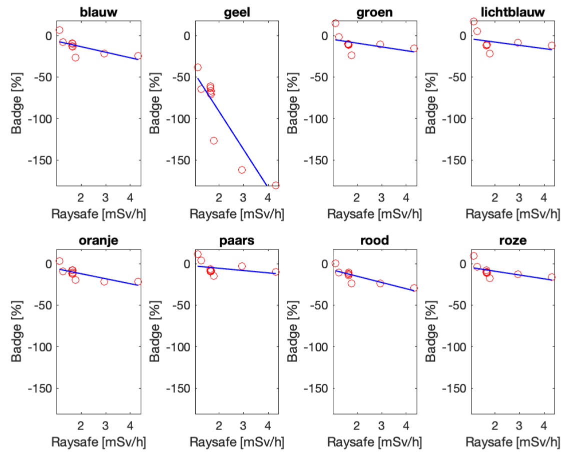

Figure 4: Percental difference between the doserate measured by the Raysafe and by the DoseAware badges

The Raysafe was employed in various measurements to examine the presence of an inverse quadratic relationship between distance and dose rate. Figure 5 displays an inverse quadratic function plotted at the measurement points, confirming the existence of this correlation. The relationship between increased dose rates leading to larger deviations can be combined with this correlation. Since the measurements will be conducted at distances of 50 centimetres and beyond, a lower dose rate will be detected, resulting in smaller deviations. This indicates that the badges are suitable for use in the actual measurement setup.

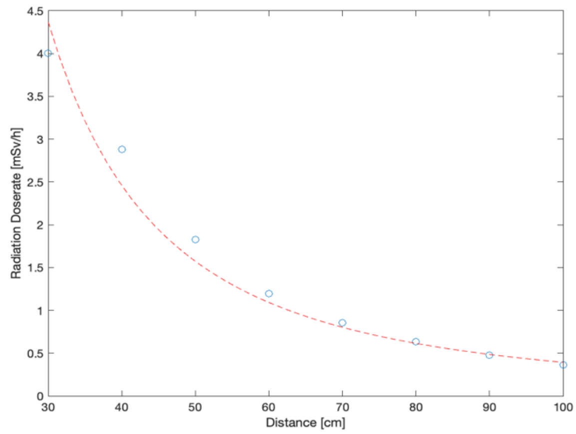

Figure 5: Plotted relation between the distance and the measured doserate by the Raysafe

Additionally, it was discovered that some measurements were not recorded in their entirety. The measurements were conducted over 10-second intervals, and mainly for the lower dose rates, there were instances where no radiation was detected during certain seconds. Also, there were occasional instances of unexpected and unrealistically high measurements.
Moreover, the initial and final seconds of a measurement displayed a lower dose rate compared to the middle seconds. There are several potential explanations for this observation. One possibility is that radiation is not emitted throughout the entire second, resulting in a lower average dose rate during that time. Alternatively, the C-arm emitter may experience a slight reduction in radiation output at the beginning and end, as in a warm-up and cool-down period.

Measurement set-up

Measurements were conducted in the catheterisation laboratory in the Reinier de Graaf Gasthuis, simulating a realistic procedural setup as closely as possible. The C-arm that is used for this project was the Philips Azurion [36]. In this setup, the bed is positioned at a height of 88 cm (which is represented as ±0 cm in the system), and lead flaps are placed on the side, similar to those used during actual procedures. These flaps can be seen in the pictures of the setup in Appendix B.

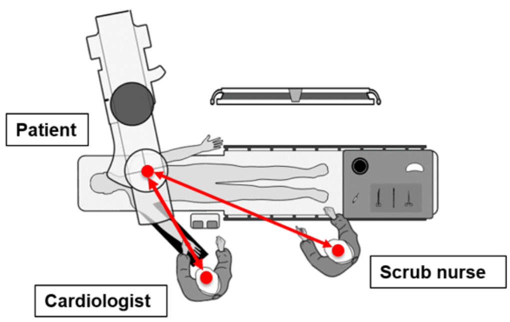

Figure 6: The average distance between the clinician's head and the source (using the patient's head as a reference)

In a study by Vijfvinkel et al., the average distance between the clinician's head and the source (using the patient's head as a reference) was found to be 103 cm [37]. For the assistant or scrub nurse, the average distance was 158 cm, as illustrated in Figure 6. These findings informed the determination of measurement locations.

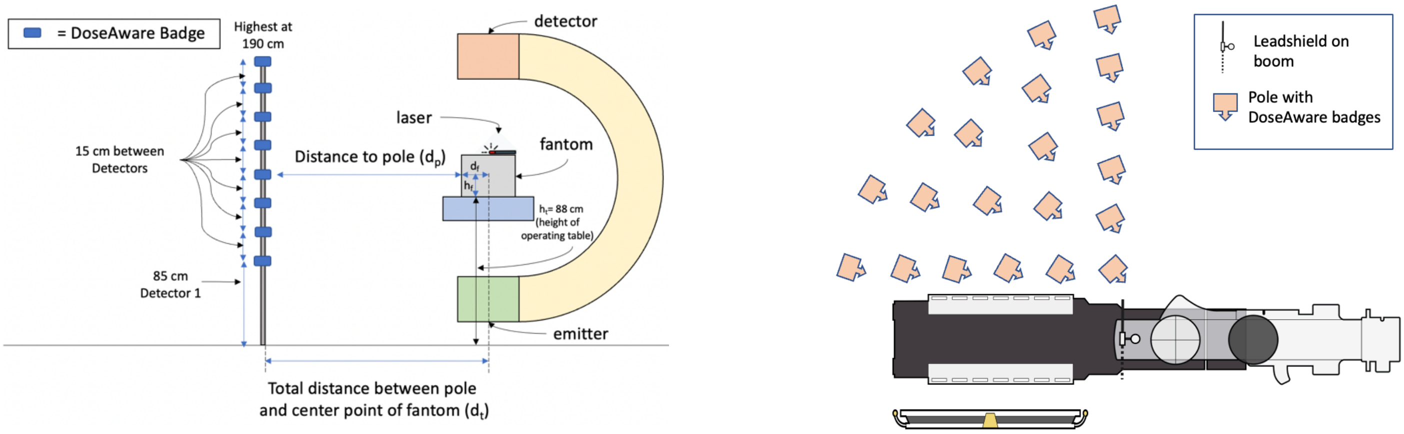

Figure 7: Measurement set-up. In the left figure the lateral view is showed with the 8 badges on the pole, the fantom and the C-arm. The right figure shows the locations of the pole in the room, where the pole for every measurement is directed at the fantom.

Eight badges were affixed to a pole, which was placed at various points within the room as is showed in Figure 8. The badges were suspended at heights ranging from 85 cm to 190 cm in 15 cm increments along the pole. The PDDs were mounted on a tilting clamp, allowing them to be angled perpendicular towards the source, which in this case was the centre of the phantom, depending on the pole's distance from the source. A protractor with a swing arm, used in conjunction with a weighted string, was employed to obtain the correct angle. The string indicated the perpendicular downward direction, while the protractor enabled accurate angle determination.

Figure 8: The eight DoseAware badges affixed to the pole

The pole was positioned at different locations, starting at a horizontal distance of 30 cm from the bed and a minimum distance of 46.5 cm from the bed's centre (perpendicular to the bed's orientation). From this point, the pole was moved 20 cm upward along the bed's edge while maintaining a consistent distance from the source at other angles. This approach allowed for the measurement of six different distances across 21 pole locations. The pole's locations were predetermined, and its placement was guided by a laser that measured the distance and aligned it with the correct angle to the phantom. The laser range finder used was the Bosch DLE Professional [38].

The angle was determined using a degree circle affixed in the centre of the top of the phantom. During this process, the laser was positioned at the pole's midpoint. Then, the pole was rotated while staying on the same place, to align the dosimeters with the phantom. The pole was rotated so that the laser was centred on the badge. By tilting the badges to account for height differences and directing them toward the source, the radiation's angle of incidence was minimised.

Ultimately, the exact location was determined by subtracting the distance between the badge and the pole from the distance between the source and the pole. The distance between the pole and the phantom was recorded in an Excel file.

The phantom utilised was composed of square slices of polymethylmethacrylate (PMMA or Perspex) measuring 30 x 30 cm, with a total thickness of 20 cm when stacked. Perspex is a widely used material for simulating the human body [39]. The lead screen was

positioned 20 cm from the phantom's side, making it 35 cm from the phantom's centre. The screen did not have any horizontal or vertical tilt. The lowest side was 10 cm above the bed's top, and the left side (the side without the cut-out) was 22 cm from the bed's side, or 47 cm from the phantom's centre. Photos of the setup can be found in Appendix B.
The test was initially conducted with an Anterior Posterior (AP) C-arm orientation, meaning the emitter was beneath the bed and the detector was above the bed. Subsequently, the test was performed with a 40-degree tilt to the left. This tilt was observed from the bed's side, opposite to the C-arm, with the detector tilted 40 degrees to the left. The Source-Image Distance (SID) used was 88 cm. The centre of the radiation beam went through the centre of the phantom, which was accomplished using a string and several dots on both the scanner as the phantom (Appendix B).
The imaging employed the following settings:

- Main Application: Cardio
- Application: Cardiac
- Procedure: Coronary 15 fps Medium
- Patient type: Normal (70 - 90 kg)

Additional settings were automatically determined based on the attenuation of the materials between the source and the detector (the phantom). Measurements were taken for 10 seconds in both acquisition mode and fluoroscopy mode. Acquisition mode, captures high-resolution, sequential images of the heart in real-time, allowing for detailed analysis of the cardiac structure and function. These images are stored for later review and typically have a higher frame rate, providing clearer visualisation of heart movement. Fluoroscopy mode, on the other hand, uses continuous low-dose X-ray beams to produce real-time, live images, enabling clinicians to observe and guide procedures like catheter placement and stent implantation; however, it provides a lower resolution and frame rate compared to acquisition mode. The tube voltages and currents for both modes can be found in Table 1. The cause for using different tube voltage and tube current settings in the oblique orientation is to maintain a certain image quality as the X-rays must pass through varying thicknesses.

	AP	40 degrees
Acquisition mode	Tube voltage: 66 kV Tube current: 393 mA	Tube voltage: 73 kV Tube current: 691 mA
Fluoroscopy mode	Tube voltage: 74 kV Tube current: 4.8 mA	Tube voltage: 99 kV Tube current: 3.6 mA

Table 1:The tube voltages and currents for both modes and both C-arm orientations

Combinations of fluoroscopy or acquisition mode, anteroposterior (AP) view or a 40° tilted view of the C-arm, and the presence or absence of a lead screen, resulted in eight different setups, with each 168 measurements.

Modelling

Python was used for data processing, modelling the (effect of the) lead screen, and the visualisation of the data [40]. Not every step of the code will be explained in this methodology section. However, some aspects that are important for the research results will be discussed. During the programming process, care was taken to ensure that the model could be easily enhanced in the future. This has been achieved by utilising functions and dividing the model into distinct stages. Consequently, if any stage requires improvement, it can be easily accomplished without affecting the rest of the code.

During the test day, not all measurements were consistently captured, especially for those with low dose rates. Consequently, it was decided to conduct 10-second measurements. As the beginning and end of the measurements sometimes yield lower values than expected, and occasional unexpected outliers were present, these factors were taken into account. For each measurement, the non-zero elements were sorted in descending order.

If there were 7 or more seconds of measurements received, an average was calculated from the third value in the row to the second-to-last value in the row. If there were 3 to 6 seconds of measurements, the median was taken. If only 1 or 2 seconds of measurements were available, their average was calculated. This approach compensated for the outliers.

All data sets (acquisition mode/fluoroscopy mode, AP orientation or 40-degree tilt orientation of the C-arm and with or without screen) were further processed. As the goal was to predict the effect of the lead screen, the screen was modelled. The boundaries of the screen, including the cut-out in the bottom corner, were precisely defined. Then the location of the screen in the measurement set-up was incorporated into the code. Subsequently, an attenuation grid needed to be established, which first required defining the source. Three possible options were tested as the source:

- **The centre of the phantom (point source)**
- **The point in the phantom where 50% of the scattering has been generated (point source):** In order to estimate the distance where 50% of the scattering has occurred within a PMMA (polymethyl methacrylate) phantom, the concept of the half-value layer (HVL) is used. The HVL represents the thickness of a material needed to decrease the intensity of radiation by half. Based on NIST data, the mass attenuation coefficient for Compton scattering in PMMA at 66 keV is approximately 0.24 cm^2/g. PMMA has a density of around 1.18 g/cm^3.

  First the linear attenuation coefficient (μ) for Compton scattering in PMMA was determined:

  $\mu = (\mu/\rho) * \rho$

  $\mu \approx 0.24 \text{ cm}^2/\text{g} * 1.18 \text{ g/cm}^3$

  $\mu \approx 0.2832 \text{ cm}^{-1}$

  Next, the HVL was calculated using the following equation:

  $HVL = \ln(2) / \mu$

  Inserting the value of μ, the following HVL was obtained:

  $HVL \approx 0.693 / 0.2832$

  $HVL \approx 2.45 \text{ cm}$

  As the thickness was desired at which 50% of the scattering develops, the HVL was used an approximation. Consequently, approximately 2.45 cm of PMMA was necessary for the development of 50% of the scattering at 66 keV. The same was calculated for the other tube voltages. The highest tube voltage (99 keV) gave an HVL of 3.09 cm with a mass attenuation coefficient of $\mu/\rho \approx 0.19 \text{ cm}^2/\text{g}$. The HVL used was at 3 cm height from the bottom of the phantom.
- **The whole phantom (3D source):** In this case every point within the phantom was seen as an equal part of the source.

After defining the source, the attenuation grid had to be populated. For the point sources, this was achieved by “drawing” a line from each point in the grid to the source point and determining whether it passed through the lead screen. For the 3D source, this process was carried out for each point in the source and then divided by the number of points. In this case, the percentage of points within the source was examined that were 'visible' for a specific point in the grid. The grid for point sources consisted of zeros and ones, while the grid for 3D sources contained fractions. These grids were then multiplied by the fraction obstructed by the lead screen.
The lead screen has a lead equivalency of 0.5 cm Pb (lead). The shielding ability of materials like lead to attenuate radiation is also described using the HVL concept and depends on the energy. Using similar calculations as mentioned previously, the following percentages of blocked radiation have been determined:

- 66 kV: 97.44 %
- 73 kV: 96.84 %
- 74 kV: 96.75 %
- 99 kV: 94.68 %

For the 3D source, this resulted in an attenuation grid as shown in Figure 9. The colour depends on the extent of radiation attenuation at that location.

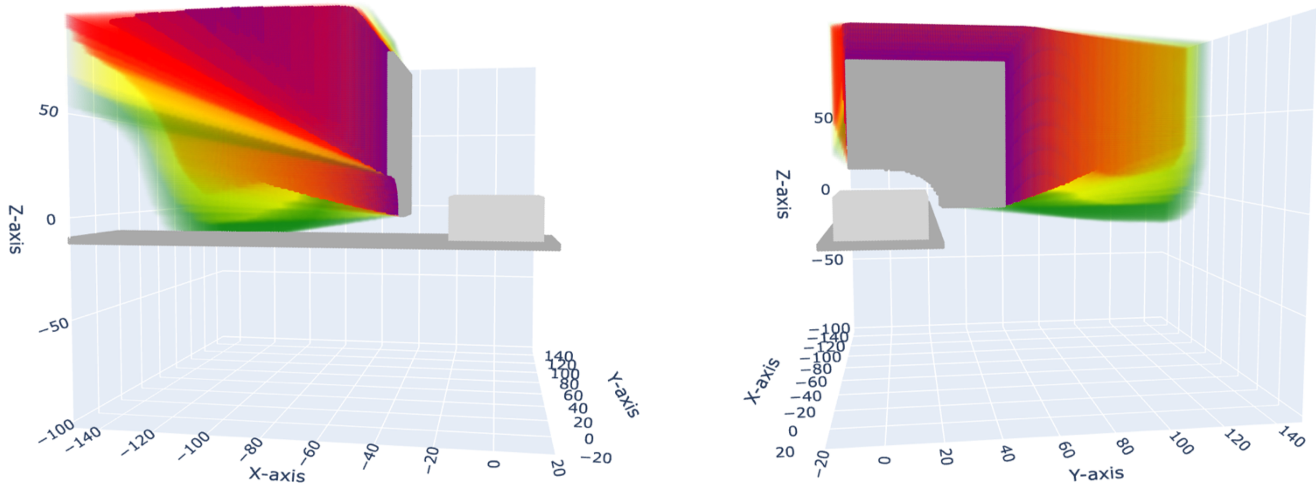

Figure 9: Visualization of the attenuation of the shield. Purple: Attenuation between 75 and 100%, Red: Attenuation between 50 and 75%, Yellow: Attenuation between 25 and 50%, Green: Attenuation between 10 and 25%

To evaluate the adequacy of the estimated dose rates with a lead screen, the differences were displayed using two boxplots. One boxplot shows the difference between the estimated and measured dose rates in mSv, while the other boxplot presents this difference as a proportion by dividing it by the measurement of each respective point. Additionally, the number of correctly estimated points was counted, with a point considered correct when the estimation fell within 0.1 mSv/h difference of the actual measurement. Using the boxplot and the number of correctly estimated points, the source type has been chosen.

The 3D source was selected as the preferred option for radiation dose estimation due to several reasons. First, it demonstrated higher accuracy across various conditions, such as acquisition AP, acquisition with a 40° tilt, and fluoroscopy with a 40° tilt. Second, the distribution of deviations was smaller for the 3D source, indicating that estimations were closer to the actual values. Third, the 3D source offers a more comprehensive representation of the radiation field, which can potentially lead to better estimation accuracy. Lastly, the 3D source may be more adaptable to different clinical scenarios, making it a more versatile option for radiation dose estimation in practice.

The data was interpolated to estimate the dose rate at each point in space, which then was utilised for assessing the clinician's exposure and visualising the protective effect of the lead screen. To achieve this, the measured data without the lead shield was first interpolated, and subsequently, the attenuation effect of the lead screen was incorporated. Various interpolation and extrapolation techniques were examined to determine their suitability for the dataset.

- Trilinear interpolation: Trilinear interpolation is a method of interpolating data points within a 3D space. It extends the concept of linear interpolation and bilinear interpolation to three dimensions. In trilinear interpolation, the data is sampled at eight neighbouring grid points of a cubic cell, and the value at an arbitrary point within the cell is estimated as a weighted average of these eight data points. The weights depend on the relative distance of the point to each of the eight grid points.
- Nearest-neighbour interpolation: Nearest-neighbour interpolation is the simplest method of interpolation, applicable to 3D spaces as well. It assigns the value of the nearest data point to the point being interpolated. In other words, the interpolated

point takes the value of the closest sampled point in the 3D grid.

- Inverse Distance Weighting (IDW): IDW is a weighted average interpolation method where the influence of sampled points on the interpolated point is inversely proportional to their distance. In 3D interpolation, the weight assigned to each sampled point is determined by the inverse of its distance to the interpolation point raised to a certain power. The interpolated value is then the sum of the product of the weights and sampled values, divided by the sum of the weights. The power parameter determines the degree of influence that the sampled points have on the interpolated value.
- Radial Basis Functions (RBF): RBF interpolation is a technique that uses radial basis functions as basic functions to represent the spatial relationship between data points in 3D space. The value at an interpolation point is computed as a weighted sum of radial basis functions centred on the sampled data points. The weights are determined by solving a system of linear equations formed by the values of the radial basis functions at the sampled points. RBF interpolation can capture complex spatial patterns and produce smooth interpolated surfaces.
- Kriging: Kriging is an interpolation method that considers not only the distance between sampled data points but also their spatial correlation to estimate values at unsampled locations. In 3D interpolation, kriging computes the interpolated value as a weighted linear combination of the sampled data points, with weights determined by minimising the variance of the estimation error while ensuring the weights sum to one. Kriging relies on a semi-variogram, which quantifies the dissimilarity between data points based on their separation distance and direction.
- B-spline interpolation: B-spline interpolation is a method that uses B-spline basis functions to represent the spatial variation of data points in a 3D space. B-splines are piecewise-defined polynomial functions that are smooth and have local support, which means they are non-zero only within a specific interval. In B-spline interpolation, the data is approximated by a continuous function formed by the weighted sum of B-spline basis functions. The weights, or control points, are determined by minimising the difference between the original data and the interpolated function.

Ultimately, kriging was chosen due to its effectiveness in modelling spatial dependence between data points using a semi-variogram. This measures the degree of correlation between the differences in values of a variable at two locations as a function of the distance between those locations [41] [42]. In other words, it assesses how similar or dissimilar two points are based on their separation distance. Additionally, kriging is adaptable to anisotropy, allowing it to capture directional trends in the data and provide accurate interpolation results.

Other methods were considered but were either unsuitable for the dataset or computationally challenging to implement. Trilinear interpolation, although computationally efficient, can lead to less accurate results when dealing with radiation dose rates in a cathlab due to its assumption of a linear relationship between data points along each axis. Nearest-neighbour interpolation was found to be too simplistic for this application. The B-spline method, a 2D interpolation technique, was not used because applying it to a 3D model would require multiple 2D interpolations for each layer, which was undesirable. Radial Basis Functions (RBF) and Inverse Distance Weighting (IDW) were computationally too demanding for the available computer resources.

After interpolation, the data was visualised to examine the attenuation effect of the lead shield. Furthermore, by considering the average distances between the assistant and cardiologist, their respective radiation doses were calculated. Radiation exposure was assessed at two locations: the chest, where current badges are placed, and the head, as literature suggests this is where clinicians in the cathlab experience the most negative effects. The height of the head was set on 165 cm above the ground and the height of the chest at 140 cm and the distance from the side of the bed was put on 5 cm. The location in the room was based on the tests mentioned before and shown in Figure 6.

The conventional approach to placing ceiling-mounted shields is to position them close to the radiation source as this would optimise the "radiation shadow" of the shield [18]. However, more recent literature indicates that the lead shield should be situated closer to the operator [43]. On the other hand, an article of Klein et al. points out that when the shield is placed nearer to the operator, it provides less effective radiation protection for other individuals in the room [44].
Therefor the exposure calculation was performed for three lead screen positions and for a scenario without the lead screen: close to the clinician (20 cm from the end of the phantom), close to the phantom (5 cm from the end of the phantom), and at the edge of the phantom (0 cm from the end of the phantom). This assessment has been carried out for both the AP view and the situation in which the C-arm was tilted at a 40° angle.

If a closer look at the programmed model is desired, please contact the email address provided in the opening section of this document.

Feedback Method & Questionnaire

First, a literature review was performed to identify existing methods for radiation exposure feedback mechanisms, which can be found in Appendix A. Additionally, frequent observations were conducted in the cathlab to identify opportunities for improving the radiation feedback. By examining the challenges in implementing radiation measures, the potential solution of providing advice on the placement of the lead screen was developed.

To explore how doctors prefer to receive radiation feedback, a questionnaire has been administered to a group of interventional cardiologists at Reinier de Graaf Gasthuis, a large regional hospital. Through this survey, their opinions on general radiation safety and evaluation on various radiation feedback possibilities were gathered. The following techniques were assessed based on methods identified in the literature review. Additionally, potential novel techniques were explored and evaluated. These new techniques were devised by regularly attending the cathlab during different types of procedures. This entailed identifying opportunities to communicate the received radiation dose or possibly give advice on how to better use certain measures without disturbing the clinician.

- A bar graph: The dose data is displayed separately for each person present and includes current dose rate (mSv/hour), accumulated procedure dose (mSv) and accumulated annual dose (mSv). The current dose rate is shown in colour bars, which increases in size and changes colour as the radiation thresholds changes.
- A sound: This sound can be heard upon receiving radiation, where the bleep rate increases with higher radiation levels.
- A wearable: This wearable shows the real-time doserate and will vibrate when this doserate is higher than a certain threshold.
- Augmented Reality: This is a technology that superimposes a computer-generated image on a user's view of the real world. In useful embodiments, a head-mounted display of several radiation zones is used, which can be conveyed to the user by such means as display glasses, overhead displays, projections or by showing it on a monitor.
- Instructions for the lead screen: In this case the clinician will get directional advice on how to place the lead screen. This can either be shown on the lead screen or on the monitor.

The questionnaire can be found in Appendix K.

Results

Measurements & Processed data

For the fluoroscopy measurements in the AP orientation, one recording (thus eight measurements, as there are eight badges on the post) did not go as planned. Both with and without the lead screen, these two setups resulted in 160 measurements. Out of the in total eight setups, the other six were successful, each comprising 168 measurements. These measurements have been visualised as scatterplots demonstrated in Appendix D. The x, y, and z-axes (in centimetres) remain constant over the plots in this report, as shown in Figure 10, where coordinate 0,0,0 corresponds to the centre of the phantom.

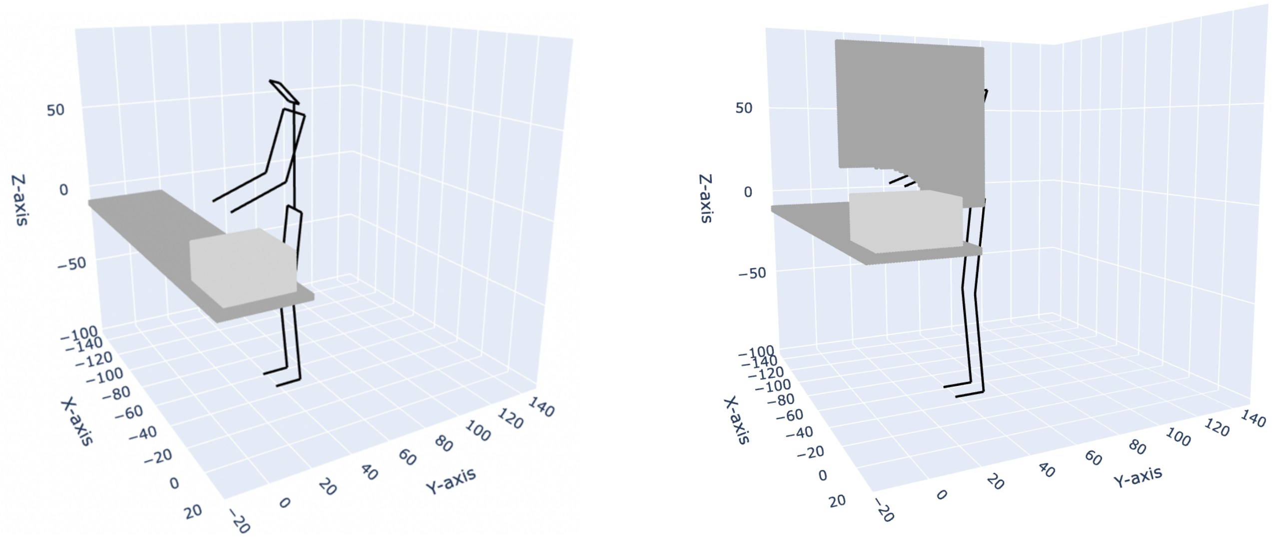

Figure 10: Coordinate system of the measurements in the Catheterisation Laboratory, with the bed, the phantom and on the right lead screen

To gain a better understanding of how these measurement points are distributed in the space, the interpolated data for all measurements can be found in Appendix E and Appendix F. From these visualisations, it is evident that the dose rate is higher when the acquisition mode is used. Additionally, the radiation levels are observed to also be higher when the C-arm is rotated by 40 degrees.

To determine whether the measurements align with the expected values, an inverse square relationship was examined, which was found to be valid for all measurements in the line perpendicular to the bed and closest to the source (Appendix C). Furthermore, the attenuation directly behind the screen was assessed to verify if it matched the anticipated attenuation. The dose rates and attenuation are outlined in Table 2. It can be observed that the attenuation corresponds with the expected values in the acquisition mode, but in the fluoroscopy mode, there is a lower decrease than expected for both orientations of the C-arm.

	(x, y) Without lead screen	(x, y) with lead screen	Dose rate without lead screen [mSv/h]	Dose rate with lead screen [mSv/h]	Percentage of reduction	Expected percentage of reduction
Acq, AP	(-44, 41)	(-45,40)	1.1419	0.0439	- 96.1 %	- 97.4 %
Fluo, AP	(-44, 41)	(-45,40)	0.1865	0.0495	- 73,5 %	- 96.8 %
Acq, 40°	(-44, 41)	(-45,40)	3.3601	0.2488	- 92.6 %	- 96.8 %
Fluo, 40°	(-44, 41)	(-45,40)	0.5016	0.2791	- 55.6 %	- 94.7 %

Table 2: Comparison between expected and actual attenuation of the lead screen

The shield was incorporated into the measurements without the use of the lead screen, and the quality of the estimations was compared to the measurement points that already included the shield. This approach was applied to three different source types mentioned in the methods, namely the Point Centre of the source, Point Low in the source, and the 3D source. The accuracy of the estimations was evaluated based on whether they were within a deviation of 0.1 mSv/h from the actual measurements. In that case the estimated point is considered correct. This data, along with the spread of the difference showed in boxplots are shown in Appendix G.

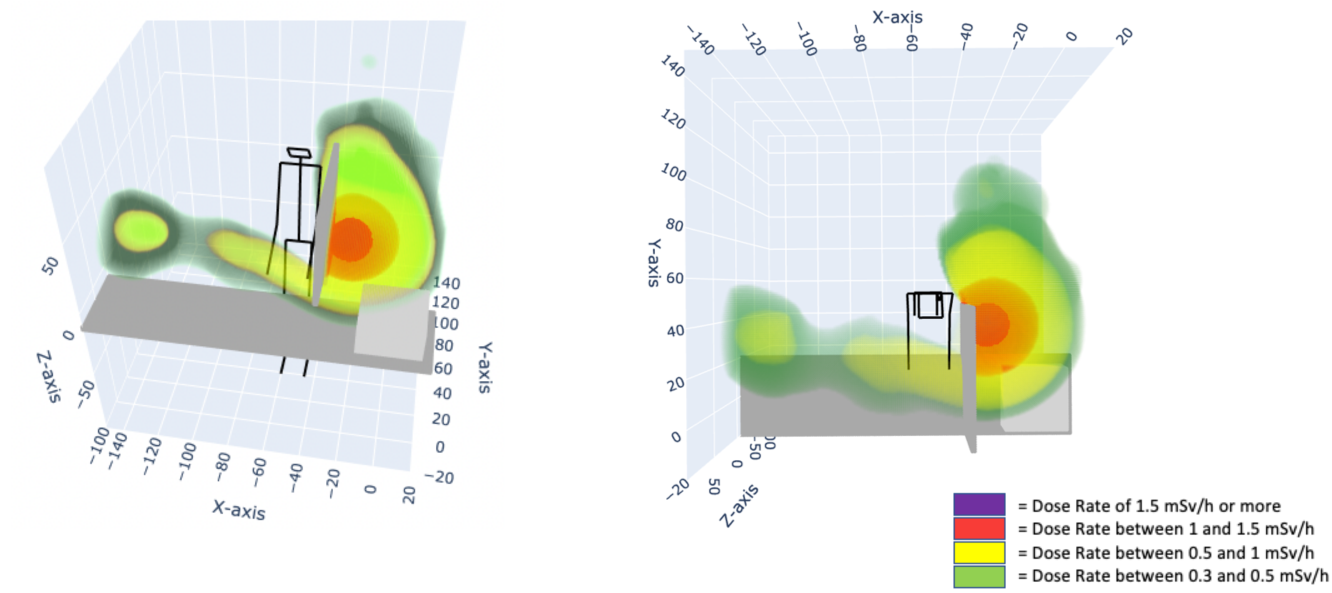

Figure 11: Measurement data without the shield combined with the estimated attenuation of the lead screen. AP orientation C-arm, Acquisition mode. Lead screen placed 20 cm from the phantom.

The results for each source type and condition are summarised below:

- In the Acquisition AP mode (total points: 168), the estimation accuracy was highest when the point source was at the height of the 50% attenuation (133 correct), followed closely by the 3D source (132 correct) and the point in the centre of the source (128 correct). The distribution in the boxplot was comparable for each condition. For the 3D source, most data points were closer to 0% deviation in comparison to the other two, but there were also larger outliers.
- In the Fluoroscopy AP mode (total points: 160), the estimations were consistently accurate across all source types, with each condition yielding 160 correct estimations. The distribution in the boxplot was also quite similar for each condition.
- In the Acquisition mode with a 40° tilt, the estimation accuracy was highest for the 3D source (82 correct), followed by the point in the centre of the source (70 correct) and the point lower in the source (67 correct). The distribution in the boxplot was smaller for the 3D source compared to the other two conditions.
- In the Fluoroscopy mode with a 40° tilt, the estimation accuracy was highest for the 3D source (142 correct), followed by the lower point in the source (138 correct), and then the point in the centre of the source (134 correct). The distribution of differences was smaller for the 3D source compared to the two point sources.

These results provide insights into the accuracy of radiation dose estimations under different scenarios and have led to pick the 3D source as the representation of the source in the model.

The inaccurately estimated values were interpolated and plotted in Appendix H. In these visualisations, blue areas represent instances where the estimation provided a dose rate of at least 0.1 mSv/h lower compared to the measurements, indicating that the model overestimated the amount of radiation blocked. Conversely, red areas signify cases where the estimation yielded a dose rate of at least 0.1 mSv/h higher compared to the measurements. Notably, in the fluoroscopy with anteroposterior (AP) orientation of the C-arm, no areas were visualised, as all the differences were lower than 0.1 mSv/h. By combining the radiation data from measurements without the lead shield and the attenuation model described in Figure 9, an estimation of the attenuation can be visualised as shown in Figure 11. This process was carried out for the lead shield positioned in three locations, as detailed in the methods section. Appendix I provides visualisations of how the radiation spreads in the room at different lead shield positions. In Figure 12 the effect of the placement of the lead screen can be seen, when you compare it to Figure 11.

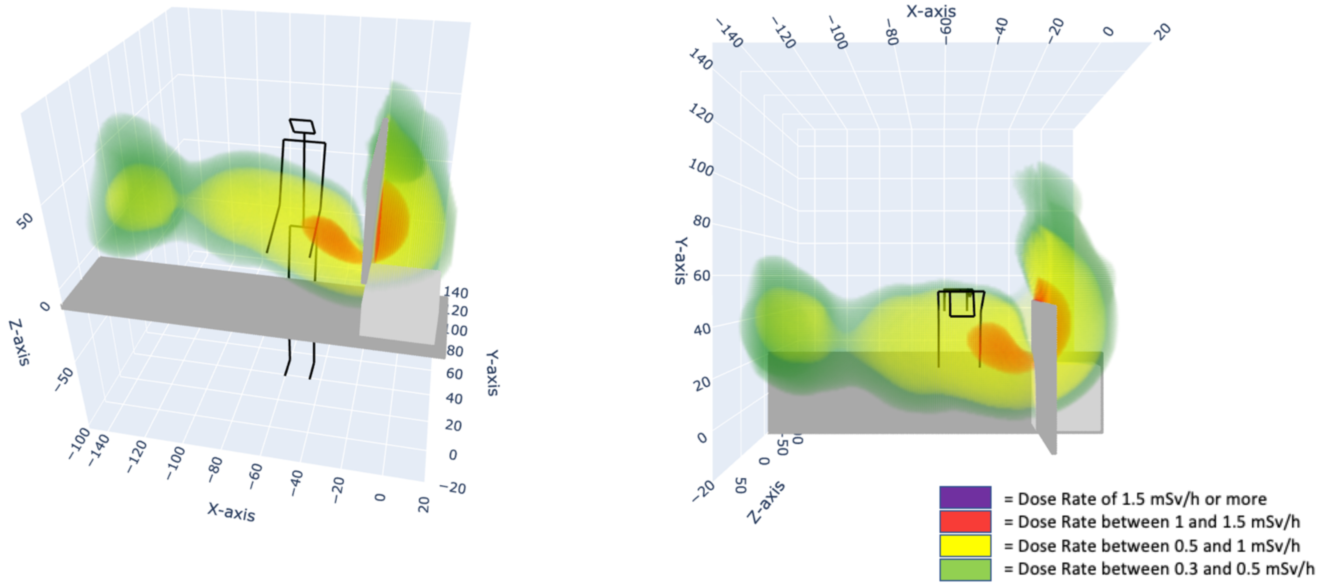

Figure 12: Measurement data without the shield combined with the estimated attenuation of the lead screen. AP orientation C-arm, Acquisition mode. Lead screen placed 0 cm from the phantom.

The percentage of the attenuation of the dose rate for the chest and head of clinicians, relative to the measurements without the lead shield, is presented in Table 3. This represents a 6.2-fold and 2-fold increase in radiation attenuation for the chest and head respectively, given the lead shield is correctly utilized.

It can be observed that the amount of radiation exposure, particularly for the interventional cardiologist, increases as the lead shield is positioned closer to the radiation source. Table 4 and Table 5 in Appendix J outlines the dose rate for various procedural settings combined with the location of the lead shield. Here it can be seen that placing the lead screen closer to the clinician, rather than closer to the source, could potentially result in a dose reduction up to 32.5 times for the chest and a 20 times dose reduction for the head.

	Location	**Attenuation with shield on spot measurement (20 cm to phantom)**	**Attenuation with shield closer to phantom (5 cm to phantom)**	**Attenuation with shield next to phantom (0 cm to phantom)**
Interventional Cardiologist	Chest	97.4%	32.3%	15.6%
	Head	97.4%	67.3%	47.5%
Assistant / Scrub nurse	Chest	4.2%	0.8%	0.4%
	Head	31.5%	7.7%	3.7%

Table 3: Expected attenuation of the dose rate for Interventional Cardiologist and the Assistant, with the lead screen on three different locations. The percentages represent the expected reduction in radiation exposure compared to the measurements without the lead screen.

Feedback Method & Questionnaire

A questionnaire was conducted with five interventional cardiologists to gather insights into their current radiation safety practices. The results of the questionnaire are in Appendix K, however the results revealed several key points which are detailed below.

The first part was regarding the current radiation safety measures. Radiation safety is deemed highly important during a procedure, with an average score of 8 out of 10. In terms of protective equipment, all five cardiologists consistently wear a lead apron and collar. Only one individual always wears protective glasses, and one other wear them occasionally.

The lead screen, an essential component for shielding against radiation, is utilised with different reasons among the respondents. Four out of five cardiologists reported moving the screen during procedures because it obstructs the C-arm or hampers the procedure itself. One cardiologist mentioned moving the screen to achieve better shielding. Generally, there was uncertainty regarding the optimal placement of the screen, with most choosing to position it in the middle of the patient. However, one cardiologist directed it to the emitter. Additionally, three cardiologists expressed their preference for positioning the lead screen as close as possible to the radiation source. One of them stated, "I position the screen as close as possible to the centre of radiation to block as much radiation as possible, also considering the assistant."
One challenge faced by the cardiologists is manoeuvring the lead screen within the confined space of the catheterisation laboratory. The screen is a rigid object attached to an inconvenient arm on the ceiling, which makes it difficult to move around.

To reduce radiation exposure, the cardiologists primarily focus on taking short recordings and using diaphragming. However, they prioritise diagnostic accuracy and patient care above all else. Despite the challenges and uncertainties, the cardiologists appear to be making efforts to balance radiation safety with the best possible patient outcomes.

The second part was regarding the feedback of the radiation. The clinicians received a monthly report on their total radiation dose exposure for that month. However, they hardly paid attention to this information, as they believed that any potential harm had already occurred. Also, from this feedback it was unclear what factors contributed to the exposure. Also, various radiation feedback techniques where discussed. When rating the techniques on a scale from 1 to 10, the average scores for each technique are as follows:

- Bar graph: 7.3 [6.5 – 8]
- Sounds: 2 [1 – 3]
- Wearable: 3.2 [1 – 5]
- Augmented Reality with glasses: 6.5 [2 – 8]
- Augmented Reality with projection on the floor: 6.5 [4 – 8]
- Augmented Reality with projection on the ceiling: 3.4 [1 – 5]
- Augmented Reality displayed on the monitor: 7.4 [7 – 8]
- Advice on optimal position of the lead screen (displayed on lead screen): 8.6 [7.5 – 9]
- Advice on optimal position of the lead screen (displayed on monitor): 7 [5 – 8]

When asked about other possible options, a combination of Augmented Reality on the monitor and advice on the optimal position of the lead screen was suggested. This would provide clarity for both the cardiologist and the assistant on safe positioning during procedures. Furthermore, the participants expressed interest in having training sessions to provide more guidance on radiation safety. These sessions would ideally include practical lessons and feedback on real procedures in comparison to their colleagues.

Discussion

The importance of radiation safety in the field of interventional cardiology cannot be overstated, as it directly impacts the well-being of both patients and medical professionals. This research aimed to enhance radiation safety by exploring a comprehensive approach to the guidance and implementation of protective measures, thereby ensuring the safety and well-being of healthcare workers who face radiation exposure in their daily practice. A model is developed that calculates radiation scattering in the catheterisation laboratory and determines the effect a lead screen has on this radiation distribution. Also, by working with interventional cardiologists, the research explored potential methods for communicating dose rate data during procedures to increase radiation exposure awareness and encourage protective measures adoption.

Feedback strategy

The questionnaire results provided valuable insights into the current radiation safety practices of medical professionals and their perception of potential feedback methods. The participants rated the importance of radiation safety during procedures an average of 7.6 [4 – 9], highlighting their awareness of the issue.

From the questionnaire, several conclusions can be drawn about the current state of radiation safety among the respondents. The participants consistently wore the lead apron and collar, but there was a lack of adherence to wearing lead glasses, suggesting a potential area for enhancing personal protection.

There was ambiguity regarding the best location for the lead shield, as some put it close to the source, while other put it close to themselves. The respondents also mentioned that they move the lead shield primarily because it obstructs their workspace rather than for improved radiation shielding. This indicates a lack of understanding of the shield's optimal positioning and its importance in reducing radiation exposure.

In terms of radiation feedback, the current practice of providing monthly feedback seems to be insufficient, as respondents reported not paying much attention to it.
Among the already available feedback techniques, the bar graph scored the highest, with an average rating of 7.3. This is in line with the findings of the literature review performed before this study (Appendix A). The most preferred option was to display the suggestion of the optimal position of the lead screen directly on the shield, which received an average rating of 8.6. This indicates that there is high interest in such a method to improve their radiation safety.

The method of providing feedback on the lead screen has not yet been thoroughly investigated. Ideas include a display featuring a 3D arrow indicating how the screen should be moved. Alternatively, it might be possible to use lights along the edges to signal where the screen needs to be positioned.
A potential addition to the feedback system could be an augmented reality (AR) visualisation of the radiation effect on the monitor, clearly showing safe areas for personnel. However, it is essential to ensure that such a display does not distract from the procedure itself. According to every cardiologist interviewed, the quality of the diagnosis and the patient care remain top priority. An envisaged solution can be seen in Figure 13.

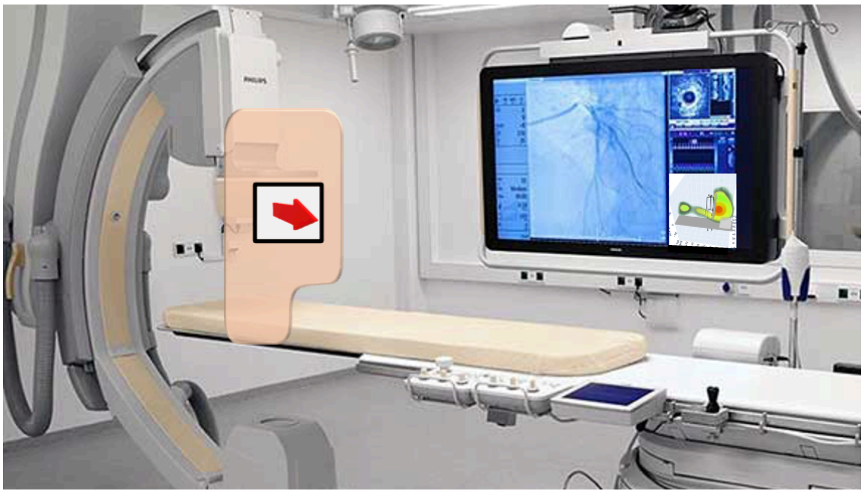

Figure 13: This figure presents a potential feedback solution. An arrow on the lead screen indicates the required adjustment, while the lower right corner of the monitor displays the effect of the current position of the lead shield.

There are several limitations to this part of the study, including the small sample size of only five interventional cardiologists and the fact that it was conducted in a single centre and user group. These limitations may affect the generalisability of the results. Further research should investigate the perspectives of professionals in other interventional areas and from multiple centres. A large-scale study that includes design requirements and the involvement of various stakeholders, such as assistants in the room, would provide a more comprehensive understanding of the issue. This approach would help identify additional areas for improvement in radiation safety practices and guide the development of more effective feedback systems.

Dose Rate Model

A preliminary model has been developed to estimate the dose rates and define the effect of the lead screen on the scatter pattern in the cathlab.

Optimal position lead screen

As mentioned above, there was a lack of clarity about the proper placement of the lead screen. According to research, 51% of intervention cardiologists do not use the lead screen correctly. In other words, there is a considerable gap between theory and practice. During the questionnaire, it even emerged that in the training they receive for radiation safety, they are advised to place the lead screen close to where the imaging is performed. As shown in Figure 45 and Figure 46, this is not the case.

By positioning the screen close to the doctor rather than close to the source, radiation attenuation for the chest increases from 15.6% to 97.4%, and for the head, it rises from 47.5% to 97.4%. This amounts to a potential enhancement of the radiation attenuation by a factor of 6.2 for the chest and 2 for the head when using the lead shield correctly.

This emphasizes the necessity for better instructions on the positioning of the lead screen, an approach that clinicians expressed willingness to adopt according to the questionnaire. When determining this optimal position, the doctor's operating area should be taken into account. For instance, the doctor must be able to reach the entry of the catheter into the patient comfortably so that they can guide the catheter. In addition, they must also have the space to be able to move the bed together with the patient.

A recommendation indicating how to move the lead screen requires both the live location of the doctor and that of the lead screen. Within the Biomedical Engineering group at TU Delft, a model that can determine the live location of clinicians is being worked on among others by R. Butler, as shown in Figure 14. The location of the lead screen could potentially be determined by using a QR code (Quick Response code). 3D localization with QR codes in the cathlab involves decoding these codes from captured images to calculate the lead screen's position and orientation relative to the camera, utilizing perspective distortion and camera parameters.
Both components will require further elaboration before being applicable in practice.

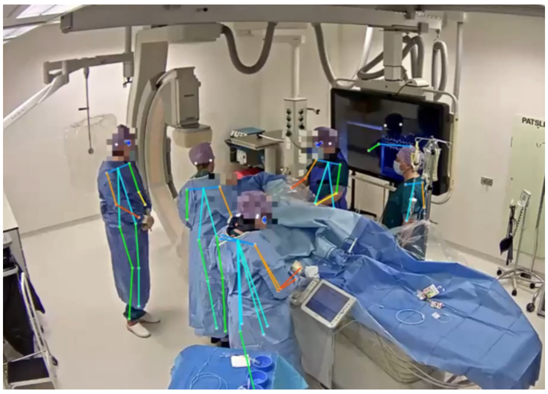

Figure 14: Localization of clinicians in the Catheterisation Laboratory

Estimation of the dose rates

The dose rates were predicted by combining the measurements without the lead screen and the expected attenuation due to the lead screen. The predictions for the C-arm in AP (132/168 and 160/160 correct for acquisition and fluoroscopy respectively) were more often correct than those of the tilted C-arm (82/168 and 142/168 correct for acquisition and fluoroscopy respectively). This is partly because the tube current is higher at the tilted c-arm (393 mA in AP vs 691 mA in 40° tilt). In addition, this occurs due to the smaller angle of scattering, which results in less energy loss. The spread of deviation in the boxplots compared with the values of the original measurements did match reasonably well.

The deviations for the acquisition mode in AP-orientation as shown in Appendix H are explainable. The estimation gives a lower doserate immediately next to the bed. So, the attenuation caused by the model should be lower. When the 3D orientation is considered, it seems that for this area, more was able to 'leak' underneath the lead screen than was predicted. The model assumed that it was only the phantom that was the source and that each point of the phantom would equally cause scattering. This is not the case, as the scattering can also be caused by other components such as the bed. Moreover, scattering will occur more at the bottom than at the top, since the higher you get, the more radiation is already attenuated. Both aspects contribute to this deviation between prediction and measurement. The red part (so the higher attenuation) is considered to be caused by radiation that would go past the lead screen in the prediction but is attenuated by the screen. It can also be a result of the interpolation. As a result, the prediction gives a higher dose rate, than the measurements.
For the fluoroscopy mode in AP orientation, all were within 0.1 mSv/h and thus considered acceptable.

In acquisition mode in the 40° tilted position of the C-arm, several areas of deviation are seen. A large proportion of these are located in front of the lead screen (on the side of the phantom). It is assumed that this is due to measurement error, as it is unlikely to be caused by the positioning of the lead screen. Research by H. Eder et al. showed that 0.15% to 0.55% of the scattered radiation impact on the operators/assistants is the result of tertiary radiation and thus neglectable [45]. The blue area behind the lead screen is similar in location and shape to the anomaly in AP mode and is probably due to scattering closer to the emitter (caused by the table and at the bottom of the phantom). The red area next to the table is difficult to explain how the discrepancy is caused there, since the (predicted) lead screen does not affect that location in the grid.
For the fluoroscopy mode in 40° tilted position of the C-arm, the deviations are at the bottom and top of the measurement values. Here it looks like a difference due to an interpolation or measurement error but remains unclear.

In short, the deviations found in the AP orientation of the C-arm are well explainable. The deviations in the 40° tilted position of the C-arm are larger and both the source should be generated differently, and the measurements should be more accurate to be ready for real-world use. However, the limit of 0.1 mSv/h is an arbitrary limit for the correctness of the prediction. The maximum of the measurements was for the C-arm in AP 1.9 mSv/h and 0.2 mSv/h for acquisition mode and fluoroscopy mode respectively. For the 40° tilted orientation of the C-arm, this was 4.6 mSv/h and 0.7 mSv/h respectively. It is therefore also logical that the measurements in fluoroscopy mode are more often correct than those in acquisition mode.
The limitations of both the measurements and the model are discussed below.

Progress in Perspective

The field of interventional cardiology has witnessed considerable advancements in radiation safety, with numerous techniques being developed to enhance protection within the catheterisation laboratory. These approaches predominantly focus on comprehensive shielding solutions, such as suspended radiation protection systems, flexible lead sheets at the base of the screen, and remote operation automation [13]. Despite their potential benefits, many of these techniques have not gained widespread acceptance due to their interference with procedural workflow. This project addresses this issue by refining the utilisation of existing radiation shielding measures rather than introducing new, inconvenient technologies, thus ensuring safety without compromising procedural efficiency.

While there are existing methods that predict scattered radiation using Monte Carlo simulations, none of them incorporate calculations or visualisations that account for the effects of a lead screen [29]. This is a significant oversight, as the lead screen plays a crucial role in reducing received radiation for clinicians.

Positioning the screen closer to the clinician is consistent with recent literature [18]. The visualisation provided by this study can enhance real-time understanding during procedures, enabling clinicians to effectively adjust the position of the lead screen. This approach makes the implications of the screen's positioning more tangible for the medical team, ensuring optimal radiation protection. By providing actionable insights on real-time positioning adjustments, the study paves the way for proactive radiation hygiene, potentially reducing future radiation exposure for clinicians and patients.

Limitations Measurements

To obtain a more accurate impression of the model's reliability, the first consideration is the quality of the data.

Reliability of the DoseAware badges

The measurements were performed by the DoseAware badges. To minimise stand dependency, we attempted to reduce both horizontal and vertical angles as much as possible. Also, by measuring for 10 seconds, we eliminated a portion of the uncertainty associated with the measurements.

It is important to note that these badges are not specifically designed for research and precise measurements. If more reliable measuring instruments were available, it would be beneficial to repeat the same test using those devices. Additionally, the badges are not intended for high-dosage measurements, as they are primarily used for measurements under the lead apron. This could explain why there is a higher deviation from the truth in the measurements for the 40° orientation.

During the test day, we encountered a yellow badge that did not perform well. However, we still used it since it did not cause any issues during other measurement sessions. This highlights that the badges can sometimes provide unreliable data. In the actual measurements, one measurement failed, resulting in 160 measurements instead of 168 for fluoroscopy mode in AP. The missing measurement is the one closest to the source, where radiation levels are highest, potentially impacting the interpolation.

In conclusion, the measurements obtained are adequate for the objectives of this project and for assessing its feasibility. However, enhancements are required before implementing the findings in real-world settings.

Measurement set-up

In constructing the experimental setup, the simulation of real conditions was taken into account as much as possible. However, a significant difference lies in the use of a phantom instead of an actual patient. Patients produce different scattering patterns than phantoms and exhibit more variability than the predictable nature of phantoms. Although, according to the research of Edwards et al., the scatter pattern of such a phantom is reasonably comparative with a patient [39]. Furthermore, individual patients differ, necessitating patient-specific inputs for practical application of the model. As this aspect largely correlates with a patient's BMI, this could serve as an input parameter.

Additionally, the phantom is a square block, and unlike a human body, it does not attenuate radiation on its sides. During procedures, patients are also covered with a lead blanket, resulting in a lower dose for the assistant in real-life scenarios compared to the model. Another aspect not accounted for is the shielding effect provided by the interventional cardiologist, who wears a lead apron, casting a significant "shadow" on the dose rate within the cathlab.

Limitations Model

Throughout this project, the primary focus has been on developing an initial version of a model to demonstrate the feasibility. Careful consideration has been given to the ease of refining and improving the model during the programming process. Some limitations that require improvement or further investigation are described below.

Representation of the scattering source

It is important to note that this estimation relies on a simplified model. In a real-world scenario, factors such as the source's energy spectrum, and the presence of other interaction mechanisms may impact the scattering. This has implications, such as the fact that the mass attenuation coefficient varies for each energy level. The modified centre of the scattering source was the same for both orientations of the C-arm. However, this should not have been the case as it should be more towards the emitter in tilted position of the C-arm. Also, it was decided to maintain the same HVL for every tube voltage since the HVLs were very similar to one another.

For the point source where 50% of the scattering has been generated, the HVL was used to define this point. It should be noted, however, that HVL is typically used for attenuation rather than scattering specifically.

In the 3D source model, each point is assigned equal weight, although the majority of scattering occurs at the bottom (the side of the emitter) of the phantom due to the phantom's attenuation.
In future refinements of this solution, this aspect should be considered and incorporated. One possibility for this improvement, for example, is to multiply each centimetre by the fraction of attenuation caused in that area.

As discussed earlier, it is not only important to consider the increased scattering at the bottom, but also to account for other sources of scatter, such as the table on which the patient lies. Therefore, these factors should also be incorporated into the model.

Interpolation
For the interpolation of the data, Radial Basis Functions (RBF) and Inverse Distance Weighting (IDW) were computationally too demanding for the available computer resources. Both RBF and IDW consider the spatial relationship between data points in 3D. These methods should be evaluated using more powerful computing resources to determine their suitability.

Incorporating the location of the radiation source or integrating known physiological data into the model could potentially improve interpolation accuracy. For instance, based on knowledge about radiation and the findings from the test day, it was clear that without objects between the meter and the source, there is an inverse quadratic relationship. This can also be used in the model. As it stands, the current model seems to centre the radiation around the measurement point with the highest dose rate, whereas the dose should continue to increase as it approaches the phantom. Enhancing the model in this way could lead to more accurate results.

Lastly, a validation of the interpolation quality should be incorporated to determine which method works best.

Lead screen
The lead screen is modelled as a screen that attenuates the radiation passing through it based on a specific energy level. This assumes monoenergetic radiation, when in reality it consists of an energy spectrum. Moreover, the model assumes that the radiation passes straight through the screen, since the attenuation is determined by the thickness of the screen. However, if the radiation reaches at an angle, it will travel a longer path through the screen, resulting in greater attenuation. These factors should be taken into account when further developing the model.

Future Research
Further measurements
Ideally, future measurements should be conducted during actual procedures. However, this can be challenging in terms of data collection. One possible solution to get a closer resemblance to reality is to utilise a more comparable phantom that mimics the shape of a patient, complete with a lead blanket on top. Also add measurements with a mannequin with a lead apron on the position of the interventional cardiologist.

In addition, it would be beneficial to explore other lead screen positions to determine their predictability and optimise the location of the lead screen. This investigation should particularly focus on potential tilting the shield in all directions.

Another aspect warranting further examination is the adjustment of radiation settings, such as diaphragm settings, tube voltage, and others. Although there is already a wealth of literature available on this topic, it can still be utilised for refining the model.

Lastly, conducting measurements without the phantom could provide valuable insights into the effects of the table and the cone of the emitter. This approach would help isolate these factors and potentially contribute to the development of a more accurate and comprehensive model.

Determining Dose
In the current model, dose evaluations focus on the chest and head due to the TLD badge placement and clinical relevance respectively. The goal is to extend the calculations to the entire body using a dose matrix and the clinician's body coordinates, enabling accurate assessment of radiation exposure throughout a procedure. This includes considering the shielding effect of a lead apron and varying radiosensitivity of different body parts, represented by tissue weighting factors, to calculate the effective radiation dose [46].

Conclusion

Ultimately, radiation exposure poses a significant health risk to cardiologists performing interventional procedures, necessitating innovative solutions to minimise exposure. In this study, a preliminary model was developed to predict radiation exposure based on the location of the lead screen enabling the radiation dose received by clinicians during a procedure to be computed. By calculating this radiation, an optimal position for the lead screen can be determined. Feedback on this optimal position is given through instructions on the lead screen. The resulting scatter pattern is visualised on the monitor, allowing everyone in the room to prevent and thus minimise their radiation exposure. Interventional cardiologists have recognised the potential added value of this technique and are receptive to implementing it in practice. Furthermore, placement of the lead screen closer to the clinician, rather than closer to the source, could potentially enhance radiation attenuation by a factor of 6.2. This results in a possible dose reduction up to 32.5 times.

Key future objectives include collecting more data in different settings and positions of the C-arm, as well as investigating different positions and orientations of the ceiling-mounted lead screen. The progression from this theoretical setup to real-world applications also requires further investigation. Here, achieving real-time tracking of both the lead screen and the clinicians is essential. Moreover, the precise feedback mechanism should be piloted and refined to ensure seamless integration into clinical practice without distracting the clinician from the procedure itself.

Accomplishing these objectives will allow the model to play an important role in enhancing cathlab radiation safety, benefiting the health and safety of clinicians and staff.

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Appendix A: Literature Review

Radiation safety for clinicians in the catheterization laboratory

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Abstract

Background and objectives: Radiation dose during cardiac catheterisation interventions has been a topic of growing interest in interventional cardiology in recent years. As it has adverse impacts on both the patient and the medical staff, there is great interest in decreasing radiation exposure during these procedures. For instance, interventional cardiologists have a higher chance of developing cataracts, lens opacities, skin cancer and brain tumours. Radiation protection during the procedure consists of appropriate use of lead apparel, using techniques in reducing the radiation use to the patient and thereby the operator, beam angulation and repositioning yourself in the room. Unfortunately, clinicians do not realise when they receive too much radiation and can deploy certain measures. In current care, there is often monthly feedback on how much radiation the person has received, instead of during or directly after procedures. Real-time dose feedback can be a solution to give clinicians an indication of their radiation safety. This type of monitoring is upcoming; however, several types of feedback are being offered to staff. In this review the effectiveness of different possible real-time feedback methods is compared and an overview of emerging techniques is provided.
Results: The most commonly used technique was a bar graph displayed on a screen for the operator to see. Here, the current dose rate was displayed in colour bars, which increased in size and changed colour as the radiation thresholds changed. Other possible feedback mechanisms include sounds, a bracelet displaying radiation, a 2D computer graphic of the patient and table from the ceiling viewpoint, and a 3D augmented reality (AR) display with a real-time video feed of the intervention room.
Conclusion and discussion: The bar graph was the most promising technique, as it in most studies showed a significant decline in the dose for clinicians. Audible feedback also resulted in a partial radiation reduction. However, its standard use was not tolerated by the staff and appeared to be too distracting. Emerging technologies such as the use of augmented reality or heat maps will require clinical evaluation to determine whether they provide added value and do not involve adverse effects. Research needs to be conducted on a more reliable way that determines real-time the amount and where on the body the doctor receives the radiation. Further development is necessary to find the most effective method of communicating this data back to the clinician so that they can implement appropriate measures, such as how to place the lead screen or to increase distance to the source, without being distracted from the procedure itself.

INTRODUCTION

Quality assurance plays an increasing role in human medicine. In radiology, it not only involves image quality and reliability of diagnosis but also radiation safety and protection of patients and medical professionals, which is often neglected in the daily routine [1, 2]. In recent decades catheter procedures have changed the way patients are diagnosed and treated at the cardiology department [3]. Diagnostic and interventional cases require the use of X-ray images to enable the doctor to visualise the anatomical location and proper use of interventional equipment. Ionizing radiation exposure poses an inherent risk of damaging tissue at the molecular level and can cause tissue responses in both the patient and exposed personnel [4]. As the medical staff receives radiation with every procedure, occupational radiation exposure is a major concern in cardiac catheterisation laboratories. In the study of Vañó et al. they monitored the radiation exposure to medical staff in the interventional and cardiac radiology. The medical staff was monitored using nine dosemeters, which resulted in Figure 1 [5]. As more and more becomes possible within the imaging field, physicians will make use of these opportunities. This raises the question of whether the additional radiation required outweighs the benefit of imaging and if it can be reduced.

Effects Radiation Exposure

Radiation has a linear, dose-dependent risk profile for which there is no minimum safety threshold. Ionizing radiation can have either deterministic or stochastic adverse effects on human tissue. Deterministic effects occur when the dose exceeds a specific threshold. The severity of deterministic effects commonly increases with dose, as more cells are killed or damaged. Examples include infertility, skin erythema and scaling, and cataracts [7]. For instance, the lens of the eye is prone to receive high radiation doses. Consequently, an increased prevalence of cataracts and lens opacity has been observed among interventional radiologists and cardiologists [8]. Compared with those not exposed to fluoroscopy, interventional cardiologists have a threefold greater occurrence of posterior subcapsular lens opacity [9].

Stochastic effects are those for which the probability

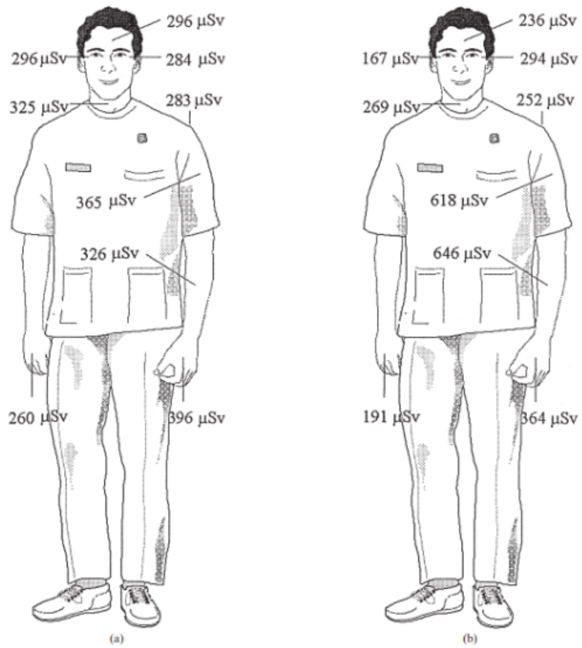

Figure 1: Graphic presentation of the mean values of doses per procedure found at the locations monitored for radiologists (a) and interventional cardiologists (b) [6]

of an effect, rather than its severity, depends on the dose of radiation received. It has a long latency period and involves no threshold dose under which genetic material remains completely intact. Typically, these adverse effects are cancers of the skin, thyroid, nervous system and gastrointestinal tract [10]. Cases of brain tumours disproportionately on the left side have also been reported in doctors performing interventional procedures. Radiation exposure on the left side of the head is known to be twice as high as on the right, which can also be seen in Figure 1. Also, the hand receives a significant amount of radiation (45-1500 µSv per procedure) during the procedures, as it is not shielded and is close to the radiation source. However, this level of exposure is unlikely to cause adverse health effects [11]. In order to minimize the risk of the clinician experiencing adverse effects, the ALARA (as low as reasonably achievable) principle will have to be adhered to ensure the clinicians radiation safety.

Potential Radiation-reducing Measures

Radiation protection consist of two parts - an active and a passive component. The passive component consists of measures that cannot be influenced during the intervention, such as (personal) protective equipment and secure devices. The active component focuses on minimising radiation during interventions, including using adjustable lead screens and adjusting imaging techniques.

Passive Processes

Passive protection strategies primarily consists of architectural and stationary shielding as well as personal protective equipment. The personal protection includes wearable aprons, thyroid collar, eye-wear, gloves and caps. While the aprons and thyroid collar are generally accepted and worn, only 30% of the interventional radiologist used the lead glasses [12]. This while eye problems are one of the common negative consequences of radiation for the operator and it can result in a radiation reduction of 35% to 90% [13]. The use of protective gloves or caps are even less accepted. Lead-containing gloves exist, but they are large and cannot be used when dexterity is required. Lead-based (or lead-free) radiation-absorbing latex gloves implemented in some centres help overcome these problems. According to Kim et al., these gloves can protect the hand by 20 to 50% but are still not widely used [14]. Lastly, the lead cap is also not commonly employed. Compared to ceiling-mounted lead shields, lead caps that cover the sides and bottom of the face have been shown to reduce radiation exposure to the head [15]. However, a lead cap weighs about 1,140g, which can further contribute to orthopaedic injury in operators [16]. Lead-free alternatives are now available, such as surgical caps containing bismuth and barium, which weigh only 53g. However, a recent study has shown that radiation scatter mainly comes from below the doctor's head and that radio-absorbent surgical caps do not cover this area. The radiation dose to the brain has been shown to decrease by only 3.3% - an almost negligible amount [17]. In addition to shielding, development in imaging devices also provides a considerable reduction in radiation. Compared with traditional fluoroscopy, relatively new image noise reduction technology enables the radiation dose to be halved [18]. In conclusion, the lead apron and thyroid collar provide good protection, but the other personal protection equipment provides either insufficient protection or are too inconvenient for the clinician to wear. To ensure the shielding of the exposed body parts, active protection strategies will have to be applied.

Active Processes

Active protection strategies include routine and appropriate use of lead apparel, using techniques in reducing radiation use to the patient and thereby the operator, beam angulation and position yourself the room. An important element is proper training of the staff, so they know where potential improvements can be made [19].
There are several techniques that can be implemented during the procedure itself to reduce the radiation dose. For instance, restricting fluoroscopy time to the time the operator is looking at the monitor. Rather than continuing to use more fluoroscopy to study the coronary arteries, review the final image hold or use a fluoroscopy loop for dynamic processes. In a similar

way, the use of high-dose modes, including boost mode, override mode or high-contrast mode, should be reduced to a minimum [20]. Modifying the frame rate of fluoroscopy can also help reduce radiation exposure but will lower the quality of the image. Typically, the frame rate is set at 15 frames per second, and it has been shown that reducing it to 7.5 frames per second leads to a significant reduction in radiation dose [20]. It has been shown that adjusting the technical settings of X-ray equipment and applying dose reduction protocols can reduce radiation exposure by 48% [21]. In addition, the radiation dose to the patient can be decreased by an optimal table positioning. Ideally, the patient should be placed further from the X-ray source and as close as possible to the image receiver. Higher table setup lowers the skin dose to the patient [22]. Tight placement of the collimator blades results in better image quality and reduces scatter radiation. Comparable outcomes can be obtained by using semi-transparent or wedge filters [23]. Due to automatic dose controls, the X-ray tube output will increase with the patient thickness. Keeping the non-target anatomy and the operator's hands out of the field of view or primary X-ray beam is important [24]. Apart from the fact that the direct radiation dose is significantly higher than from scattering, the radiator output increases due to the automatic brightness control system. This causes an unnecessary increase in radiation for both the patient and the clinician [11]. It has been shown that the angle of the tube affects the radiation dose to patients and operators. While a wide range of tube angles are possible, few of them are actually used in the catheterisation laboratory [25]. On the one hand, a larger angle means a larger trajectory through the body, with the same mechanism is deployed by the automatic dose controls mentioned before. On the other hand, it is also partly a result of non-homogeneous scattering from the body. Consequently, the dose to the clinician depends on where he stands and where the leaded shields are located.
Alongside the shielding that is part of the passive protection, adjustable lead shields are regularly present as well. These are usually made of transparent lead-based plastic that can be easily adjusted during the procedure. Accurate placement of these is key to reducing operator exposure significantly. A gap in protection is created by the patient's contour indentation and to optimize the protection, the upper body screen should be placed close to the operator and far from the scattering source. The upper body screen should be moved regularly during the procedure when the table is moved, to ensure effective protection is maintained [17]. The amount of radiation exposure depends on the distance to the source, proportional to the inverse of the distance squared to the X-ray source. Staff can reduce their exposure by a factor of four by doubling their distance from the source [26]. In closing, there are numerous ways to improve radiation safety during surgery. The problem with this active form of radiation protection is that clinicians do not realise where and when they are receiving a lot of radiation and can deploy certain measures.

Automation

Optimally, the intervention could be performed remotely, avoiding the clinician having to be located near the radiation source. Automation or robotisation is in full development and it is obvious that clinicians would receive reduced radiation as a result [27]. Robotic remote-control angioplasty where interventional cardiologists work from a shielded workstation away from the radiation source have also been shown to reduce radiation dose by as much as 96% [28]. However, the technology is not prepared for this intervention yet, nor are doctors willing to implement it [27]. It is therefore necessary to consider improving the use of currently available measures.

Real-Time Dosimetry

In current care, there is often monthly feedback on how much radiation the person has received. The thermoluminescent dosimeter (TLD) used by the medical team has the disadvantage of not immediately showing the dose accumulated during the interventional procedure, as they require a stimulus to produce readouts of their recorded doses. This can then not be traced back to one specific procedure, let alone a particular moment in that procedure. There is already a shift in progress where physicians receive notification of how much radiation dose they have received after a procedure, yet even then they cannot see in real time how much radiation they received during the intervention.
Real-time dose monitoring is also a form of active radiation protection but is not yet widely used. These digital badges can detect and record exposure and the results are available almost immediately. Since it is a relatively new feature, several types of feedback are currently being offered to staff. In this regard, it has yet to be proved which method has a beneficial effect on radiation safety for the medical personnel and whether it involves negative impacts. The goal of this review is to provide an overview of possible real-time feedback mechanisms to communicate radiation doses during the procedure.

METHODS

Search Strategy

Two systematic searches were performed. The first systematic literature search was performed in the database of Embase. The search was conducted to identify all clinical articles that discussed real-time feedback of radiation exposure for the medical staff.

Therefore, the search term consisted of four parts. The first part dealt with radiation exposure and the dose. The second part ensured that the search yielded the focus on the medical personnel, and the third part focused on the fact that the publication concerned the monitoring or dosimeters. The final part made sure that it only consisted of interventional procedures, where it was not exclusively centred around cardiology. The search term can be found in Appendix A.
Inclusion criteria for this review were: (1) Real-time monitoring, (2) Feedback given to the medical personnel, (3) Regarding interventional procedures, (4) Discussing the occupational exposure, (5) Provides comparative information on the functioning of the feedback mechanism. All articles were screened for the aforementioned inclusion criteria by title and abstract. Next, full-text screening was performed and articles that did not meet the inclusion criteria were excluded. Finally, the reference lists of the included articles were checked for cited articles that met the inclusion criteria but were not found with the initial literature search.

The second systematic search was performed with the *Espacenet patent search*. This was conducted with the objective of obtaining insights into newer techniques that have not yet been clinically studied. The search string is comparable with the first search term and is shown in Appendix A. Since only the new technologies which have not yet been clinically tested are of interest, the patents were only reviewed published between 2017-09-21 and 2022-09-21.

Data Extraction

For the included articles, data were collected about the type of feedback and the developer of the device. This allows determining the impact of the technique and whether the results depend on the provider. Subsequently, results were listed which compared the radiation dose before and after utilising the respective feedback technique.

RESULTS

Eligible Studies

Appendix B shows the selection process of the studies. After applying the search term in Embase on 21 September 2022, 289 potentially eligible records were identified which screened on title and abstract. Here 244 were excluded, mostly because the articles were not about real-time feedback. In the full-text screening procedure phase, 35/45 articles did not meet the inclusion criteria. In addition to initial search, two records were identified through the reference lists that met the inclusion criteria but were not found with the search term. In total, 12 articles were included for this review as can be seen in Appendix B.

For the patent search 372 results were found from which 345 were excluded based on the title and abstract. The main reason was that most results were detection and warning devices used during or after radiation-treatment. Upon further review, six articles remained applicable to this study.

Feedback Possibilities

From the literature, different approaches to feedback emerged. The most frequently described technique was displaying a bar graph on a monitor in the cathlab. In this regard, all those present in a cathlab carry a personal dose meter (PDM) that is connected to the monitor. The dose data were displayed separately for each PDM and included current dose rate (mSv/hour), accumulated procedure dose (mSv) and accumulated annual dose (mSv). The current dose rate was shown in colour bars, which increased in size and changed colour as the radiation thresholds changed. Green indicated a dose rate < 0.02 mSv/h, yellow indicated 0.2-2 mSv/h, and red indicated 2-20 mSv/h. This was the case with both Philips' and RaySafe's technology. In a second research of Lundvall et al. they had a questionnaire regarding the display with bar graphs [29]. The result from the focus-group interview displayed that using a real-time dose rate system was mentioned as a particularly important learning experience for knowing how to act in a radiation-safe manner. An alternative feedback technique researched was the use of a sound that could be heard upon receiving radiation by the PDM. For the Bleeper Sv device, the bleep rate increases with higher radiation levels [30]. Moreover, the device provides cumulative radiation exposure of the operator after the procedure. Another audible device was the chirping device. The chirper responds to X-rays and gamma rays of 35-1000 keV, with a peak sensitivity at approximately 75 keV [31]. Also the acoustic warning signal reported by Kamusella et al. had an increasing acoustic signal rate with higher radiation doses [32]. The results of the studies that compared the radiation dose with and without feedback are described in Table 1.

Comparative Methods

There are various approaches for describing the received radiation dose and providing a relevant comparison. The methods that are used in the included articles are described below. Generally, the personal dose equivalent, Hp(d), is an operational quantity for individual monitoring where d is the depth in millimetres. While some used the Hp(0.07), others used the Hp(10). The Hp(0.07) dose equivalent is an operational quantity for individual monitoring for the assessment of the dose to the skin and to the hands and feet. In common practice, Hp(0.07) is the most widely used feedback of radiation dose. The Hp(10) dose equivalent is an operational quantity for individual monitoring for the assessment of effective dose. There were also cases where normalisation with the dose area product (DAP) or kerma area product (KAP) was performed. The DAP is an output measurement of the total amount of radiation delivered to the patient. Air Kerma is a dose(rate) measurement of radiation at a specific defined position such as a point on the patient's skin. Ultimately, the main analysis considers whether there is a significant difference after applying the feedback method.

Additional Feedback Possibilities

Three clinical studies discussed alternative feedback methods, but did not provide the effect that it had on radiation safety and whether wearing the bracelet decreased the radiation dose. In a study by Ban et al, a prototype was tested of a real-time hand dose monitor (HDM) in the form of a bracelet. The HDM showed to be reliable to measure the radiation dose on the hand [33]. The study of Kilian-Meneghin et al. discussed a display with more comprehensive feedback of the received radiation by the medical staff as can be seen in Figure 2.

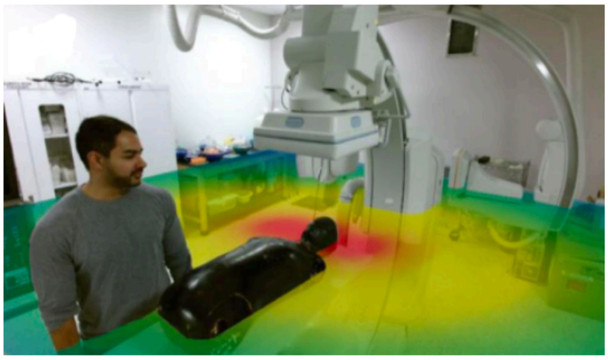

Figure 2: 3D (AR) scatter demo image featuring an anatomical phantom with a staff member in the image [34]

Two categories of scatter dose distribution displays were created for this study: a 2D computer graphic of the patient and table from the ceiling point of view and a 3D augmented reality (AR) display featuring a real-time video feed of the interventional room. The 2D display is presented as a top-down view of the interventional suite, with a colour-map of the scatter radiation values calculated one meter off the floor, a common table height. Both displays feature a colour-coded scatter field superimposed. In the survey, the 2D display featuring distance indicators received positive feedback. The questionnaire also indicated that staff position tracking and displaying individual staff dose rate estimates were desired. In this research the effects on radiation safety were not mentioned as the technique is still under development [34]. The third technique that did not yield comparative results was the feedback of radiation through a bracelet. This is a study from 2001 and after further review of available literature, no further development has been found on this technique. That potentially indicates that there is no willingness of clinicians to wear this kind of monitor.

The included findings from the patent search primarily consisted of visualizing the radiation in the room. Both Pigott John and Philips presented the possibility of using augmented reality (AR) for radiation dose monitoring. In useful embodiments, a head-mounted display is used, which can be conveyed to the user by such means as display glasses, contact lenses, overhead displays, projections or through a live image stream device. In the solution of Pigott John, the visualization comprises a continuous multi-layered cloud or sphere to display the scatter-distribution [35, 36]. Regarding Philips' solution, a radiation proximity warning can be provided to the medical staff, where the dose radiation system estimates the radiation intensity and geometry immediately prior to taking an x-ray image. The staff member that has potential of exceeding the radiation exposure limit for the planned x-ray is provided information by alerts, such as audio or screen flashes, visual display of the areas of the room that are a no-go for that staff member "painted" in a distinct colour. Also, the X-ray operator is alerted of the potential over-exposure and the staff in person is highlighted on operator's display and has to override the warning by a gesture, such as virtually clicking on the staff's avatar [37].
Siemens Healthcare generated a dose map of a region of interest in the room by applying a machine learning model to features and the interventional room scene [38]. The dose map comprises a visualization of the room overlaid by a heat map indicating areas of high dosage. It has not yet been determined to feedback the heat-map on a display, projected on the ground or other techniques. However, similar to the solution of Philips, when the operator is within an area of high dosage, an alarm will be generated for the operator.
Furthermore, Lei Zhen and Shi Cui respectively provided a solution with a monitoring device that the operator attaches to himself with a display that shows the dosage and can raise an alarm when it exceeds a certain threshold [39, 40].
Since there is no (comparative) clinical data of these additional feedback possibilities, these are not included in the table below.

Table 1: Comparative results of the radiation dose change before and after implementing the feedback mechanism

Title	Author (Year)	Feedback (Brand)	Results
Audible radiation monitors: The value of reducing radiation exposure to fluoroscopy personnel [31]	Hough, D. et al. (1993)	Personal radiation monitors that emit an audible "chirp" (Prima lb chirpers - Nuclear Associates)	The mean wrist dose for the first 4-week period was 0.81 mSv and the mean collar dose was 0.51 mSv. In the second 4-week period, when the chirpers were worn, the mean wrist dose was 0.43 mSv, a reduction of 0.38 ± 0.51 mSv, and the mean collar dose was 0.37 mSv, a reduction of 0.14 ± 0.31 mSv. This represents a mean reduction of 47% in the wrist dose and 27% in the collar dose. With a one-sided paired t- test, there was a significant reduction in wrist dose when the chirpers were used (p<0.04). The data were strongly suggestive of a reduction in the collar dose, but this reduction was not statistically significant (p = 0.11)
Reduction of radiation exposure for the examiner in angiography using a direct dosimeter [32]	Kamusella, P. et al. (2013)	An acoustic warning signal (model EDD-30, Unfors Instruments)	Over the course of 3 months, a significant improvement in the average dose rate can only be shown in the third month for the intermediate examiner. For the experienced and beginning examiner no significant difference was found.
Evaluation of the impact of a system for real-time visualisation of occupational radiation dose rate during fluoroscopically guided procedures [8]	Sandblom, V. et al. (2013)	Display with bar graph (Philips Doseware)	When the radiation dose rates were displayed to the staff, one cardiologist and the assisting nurses (as a group) significantly reduced their personal radiation doses. The median radiation dose (Hp(10)) per procedure decreased from 68 to 28 µSv (p = 0.003) for this cardiologist and from 4.3 to 2.5 µSv (p = 0.001) for the assisting nurses. However, the decrease was only for the cardiologist who had on average a high radiation dose in comparison to the other cardiologists.
Effect of a Real-Time Radiation Monitoring Device on Operator Radiation Exposure During Cardiac Catheterization [30]	Christopoulos, G. et al. (2014)	Bleeper Sv device (Vertec Scientific Ltd)	First operator radiation exposure was significantly lower in the Bleeper Sv compared with the control group (9 [4–17] versus 14 [7–25] µSv; P<0.001; 36% relative reduction). Similarly, second operator radiation exposure was significantly lower in the Bleeper Sv group (5 [2–10] versus 7 [4–14] µSv; P<0.001; 29% relative reduction). Use of the device did not result in a significant reduction in patient radiation dose.
Analysis of occupational radiation exposure during cerebral angiography utilizing a new real time radiation dose monitoring system [41]	James, R. F. et al. (2014)	Display with bar graph (Philips Doseware)	In phase II, the mean radiation dose exposure per Gy-cm2 for physician A decreased from a mean of 0.243 µSv/Gy-cm2 in phase I to 0.069 µSv/ Gy-cm2 in phase II (p<0.0001). However, physician B demonstrated a higher mean radiation dose than during phase I, increasing from 0.028 to 0.051 µSv/ Gy-cm2 (p = 0.994). The mean radiation dose per Gy-cm2 for all other roles (nurse, scrubbed technologist, and circulating technologist) decreased significantly in phase II compared with phase I.

Table 1: Comparative results of the radiation dose change before and after implementing the feedback mechanism

Title	Author (Year)	Feedback (Brand)	Results
Real-time dosimetry reduces radiation exposure of orthopaedic surgeons [42]	Müller, M. C. et al. (2014)	Display with bar graph (Raysafe)	Regarding the radiation dose, the use of DoseAware led to a significant reduction for all evaluated operation types ($P<0.05$) except trochanteric femoral fractures ($P = 0.0841$).
Effect of Real-Time Radiation Dose Feedback on Pediatric Interventional Radiology Staff Radiation Exposure [43]	Racadio, J. et al. (2014)	Display with bar graph (Philips Doseware)	Overall, the median staff dose was significantly lower in the phase where they had access to the display (0.56 µSv/ min of fluoroscopy time) than in the phase without the display (3.01 µSv/min; $P < 0.05$). The interventional radiology attending physician dose decreased significantly for procedures for which the physicians were close to the patient (median, 0.15 µSv/min [IQR, 0–3.81 µSv/min] vs 0.02 µSv/min [IQR, 0–0.83 µSv/min]; $P = 0.023$), but not for ones for which they were far away (median, 4.14 µSv/min [IQR, 2.28–16.26 µSv/min] vs 4.12 µSv/min [IQR, 0.85–5.77 µSv/min]; $P = 0.258$).
The Effect of Realtime Monitoring on Dose Exposure to Staff Within an Interventional Radiology Setting [44]	Baumann, F. et al. (2015)	Display with bar graph (Raysafe)	The overall mean staff dose per fluoroscopic minute was 42.79 versus 19.81 µSv/min ($p<0.05$) comparing the closed and open phase. Thereby, anesthesiologists were the only individuals attaining a significant dose reduction during open phase 16.9 versus 8.86 µSv/ min ($p<0.05$). Furthermore, a significant reduction of total staff dose was observed for short 51 % and interventional procedures 45 % ($p<0.05$, for both).
Combined Use of a Patient Dose Monitoring System and a Real-Time Occupational Dose Monitoring System for Fluoroscopically Guided Interventions [45]	Heilmaier, C. et al. (2016)	Display with bar graph (Raysafe i2)	A substantial decrease was found with a total mean ±SD/median KAP for both operators together (Without real-time dosemeter; 47 Gy-cm2 ±67/41 Gy-cm2 ; With real-time dosemeter, 37 Gy-cm2 ±69/34 Gy-cm2) as well as for each individual operator (for all, P 0.05).
Changes in Occupational Radiation Exposures after Incorporation of a Real-time Dosimetry System in the Interventional Radiology Suite [46]	Poudel, S. et al. (2016)	Display with bar graph (Raysafe i2)	General interventional radiology staff had a reduction in the average dose equivalence per procedure of 43.1% ± 16.7% ($p = 0.04$). Similarly, Lawrence General interventional radiologists had a 65.8% ± 33.6% ($p=0.01$) reduction while the technologists had a 45.0% ± 14.4% ($p=0.03$) reduction

Table 1: Comparative results of the radiation dose change before and after implementing the feedback mechanism

Title	Author (Year)	Feedback (Brand)	Results
Effects of real-time dosimetry on staff radiation exposure in the cardiac catheterization laboratory [47]	Murat, D. et al. (2021)	Display with bar graph (Raysafe i3)	Real-time dosimetry led to a significant reduction in operator and assisting nurse radiation exposure. During period without display the operator received 0.55 ± 0.08 µSv vs 1.40 ± 0.21 µSv during the period with display [P< 0.01]. The assisting nurse received 0.07 ± 0.02 µSv vs 0.19 ± 0.03 µSv during the period with display [P<.01]. A similar trend was observed for circulating nurses, however, this was not significant (0.02 ± 0.01 µSv vs 0.06 ± 0.02 µSv during the period without display; P = 0.23).
Does radiological protection training or a real-time staff dosemeter display reduce staff doses during X-ray guided pulmonary bronchoscopy? [19]	Lundvall, L. L. et al. (2022)	Display with bar graph (Raysafe i3)	The doses to staff which were normalised to the KAP for the patients, were not significantly altered by the use of the real-time display dose-rate meter (P > 0.05). However the staff doses per procedure Hp(0.07) (P = 0.018) and HP(10) (P = 0.043) were significantly reduced after the use of the real-time display dose-rate meter compared to the baseline. The real-time display system was found to be useful directly after the training in radiation safety, especially for facilitating understanding of how to position them safely in relation to the C-arm.

DISCUSSION

Receiving radiation dose by the clinician during cardiac catheterisation interventions is a topic of growing interest in interventional cardiology. According to the ALARA principle, this dose should be kept *as low as reasonably achievable*. Ultimately, the greatest potential benefit comes from making better use of protection, such as the movable lead shield and wearing lead goggles. However, this requires feedback to alert doctors whether they are receiving excessive radiation.

Overview of the Techniques

The most common technique described in literature is the use of a display with the dose visualised by a bar graph. Thereby, the decrease in radiation dose in almost all studies was statistically significant for at least the doctors close to the patient. In both the study of James et al. and the study Sandblom et al. there was only a (statistically significant) decrease for clinicians with an initial high radiation dose in comparison to the other clinicians [8, 41]. Thus, the results of these two studies indicate that a system for real-time visualisation of radiation dose rate may have a positive impact on optimisation of occupational radiological protection. In particular, this affects the behaviour of staff members who practise inadequate personal radiological protection.
While a bar graph provides an insightful visualisation of when the doctor receives the amount of radiation, it does not show how this compares to a similar intervention or to the total amount of radiation delivered to the patient. A possible improvement to the system would also be to compare it with other clinicians during a similar type of procedure. In a study of Crowhurst et al. a reference dose was established for several procedures. This allowed individual operators to compare their exposure with others, providing them with a simple benchmark that, if routinely exceeded, should trigger a review of their radiation safety practices [48]. By normalising the dose to the operator to the DAP (RTD/DAP), the effectiveness of radiation protection strategies can be compared as well. In this way, it would be easier to determine which doctor could make possible improvements in their radiation safety.

The findings of studies utilising audible feedback were not as promising as those using a display. In the research of Hough et al. they showed a significant reduction of the mean wrist dose, however, this was not the case for the collar dose. As shown in the introduction, the negative impact of dose mainly affects the area above the lead apron. In this regard, they indicated that radiologists were encouraged to minimise fluoroscopy time. This has the positive consequence of clinicians receiving less radiation, however, it may also result in insufficient scans being taken, resulting in less comprehensive diagnoses/interventions. In the study of Kamusella et al. in most cases there was no significant decrease in radiation dose. According to Balter S. the use of audible devices are very disturbing to the wearer and the rest of the cathlab team and cannot be tolerated for more than a few days. In addition, after contacting Raysafe and Philips, both indicated that their user research revealed that doctors want to be distracted as little as possible during these procedures. Sounds were still found to be too distracting by doctors during intervention. Ozcan et al. explored to concept of musical sonification of patient vitals and looked at ways to filter unwanted sounds and non-actionable alarms in an ICU. As ICUs are acoustically hostile environments to both the workflow for doctors and nurses and for the patient this must be improved. Sudden changes in vital signs are easily recognized by nurses and doctors by creating disturbance in music such as faster tempo or musical dissonance. "By offering musical updates to the nurses, the continuous measurement of vital signs does not create such a distraction and has a new meaning" [49]. Further research needs to be conducted on whether making sounds less distracting, similar to the solution mentioned above, could potentially be applied in providing feedback to doctors in the cathlab.

The final method that recurred in both a clinical article and in patents was radiation feedback in the form of a heat map or using Augmented Reality. However, little can yet be concluded about its impact on radiation safety since no comparative trials have been conducted (or published). There are still several possible feedback options being considered, such as displaying it on a monitor, through glasses or as a projection on the floor. The fact that it is still rarely used and clinical information about it is scarce may also indicate that the technology and/or the clinicians themselves are not (yet) ready to use it.

Limiting Factors

Comparing the studies was challenging as different types of outcome measures were used. Consequently, by normalising it with the DAP/KAP, the primary focus was on the use of protection, rather than reducing overall radiation. Ultimately, all considered whether the doctor received less radiation by applying a feedback mechanism. Thereby, it is possible to conclude that a display with a bar graph representation gives the strongest results.
Several articles indicated that it was difficult to determine whether the positive results were due to the feedback system or the Hawthorne effect. This means the phenomenon of altered behaviour of performance resulting from the awareness of being a part of an experimental study [50].
One issue is that the dosimeters used in all these researches are on a fixed position on the body. This

firstly makes it position-dependent, making it seem like you can reduce (or manipulate) the radiation by adopting a different position. In addition, it only indicates the radiation at that particular area. It may be (especially for the doctor standing close to the patient) that a specific part of the body receives a lot of radiation, while this is not accounted for in the single dosimeter on the chest. If, for instance, the lead shield protects the chest, but the head is exposed to a large amount of radiation, the clinician would not be able to receive this information. This review has not further investigated other methods of determining (more correctly) the radiation received by the clinician.

Conclusion and further research

In conclusion, there is a good shift in progress which notifies clinicians during the procedure whether they are receiving excessive radiation. More development is needed in new techniques for possible automation of (parts of) the intervention, safer equipment that requires lower radiation levels, improved protection options and lastly better feedback on how and when doctors can and should adequately protect themselves. According to research, the potential means of protection are underused and, in this regard, developing a more effective and targeted feedback mechanism may provide a solution [13]. While both the display and the sounds return the level of received radiation at a particular moment, they do not accurately reflect what measures can be taken to improve this or where on the body the radiation impacts. This is where a 2D and 3D visualisation like that in Figure 2 would be a useful solution, as you can see the effects of adjustments in the procedure itself or adjusting a lead screen. Since there are no comparative data for this, it cannot be concluded that it provides better safety for the clinician. Similar to audible feedback, the presence of this kind of monitor could potentially be too distracting for the doctor. On the one hand, research needs to be conducted on a more reliable way that determines the amount and where on the body the doctor receives the radiation. On the other hand, further analysis is required on finding the most effective method of communicating this data back to the clinician so that they can implement appropriate measures, without being distracted from the procedure itself.

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APPENDIX A: SEARCH TERM

Medbase Search

('radiation exposure'/mj/de OR 'radiation protection'/mj/de OR 'radiation dose'/mj/de OR 'radiation dose reduction'/mj/de OR 'radiation field'/mj/de OR 'radiation scattering'/mj/de OR (('occupational exposure'/mj/de OR 'occupational hazard'/mj/de) AND radiation/mj/de) OR 'personnel radiation monitoring'/mj/de OR (((radiation OR radiolog*) NEAR/3 (exposure* OR dose OR doses OR dosage* OR protect* OR fiel* OR scatter*))):ti) AND (staff/mj/de OR 'medical personnel'/mj/de OR 'occupational exposure'/mj/de OR 'occupational hazard'/mj/de OR 'interventional radiologist'/mj/de OR surgeon/mj/exp OR 'personnel radiation monitoring'/mj/de OR (staff OR personnel* OR occupational* OR operator* OR worker* OR radiologist* OR surgeon* OR medical-professional*):ti) AND (dosimetry/mj/de OR dosimeter/mj/exp OR 'thermoluminescence dosimeter'/mj/de OR 'thermoluminescence dosimetry'/mj/de OR 'radiation monitoring'/mj/exp OR (dosimet* OR dosemet* OR ((dose OR radiation*) NEAR/3 (monitor* OR rate*))):ti) AND ('heart catheterization'/de OR angiography/de OR 'interventional radiology'/de OR 'interventional radiologist'/de OR 'percutaneous coronary intervention'/de OR (((heart OR cardiac) NEAR/3 catheter*) OR angiogra* OR Intervention* OR procedure* OR cardiolog* OR Cath-Lab):ab,ti) NOT [conference abstract]/lim AND [english]/lim

Espacenet Patent Search

(ti all "radiation exposure" OR ta all "radiation protection" OR ta all "radiation dose" OR ta all "radiation dose reduction" OR ta all "mediation field" OR ta all "radiation scattering" OR ta all "occupationl exposure" OR ta all "occupational hazard" OR ta all "personnel radiation monitoring") AND (ta any "staff" OR ta any "medical personnel" OR ta any "occupational exposure" OR ta any "occupational hazard" OR ta any "interventional radiologist" OR ta any "surgeon" OR ta any "personnel radiation monitoring") AND (ta any "dosimetry" OR ta any "dosimeter" OR ta any "thermoluminescence dosimeter" OR ta any "thermoluminescence dosimetry" OR ta any "radiation monitoring") AND (ta any "heart cathetization" OR ta any "angiography" OR ta any "interventional radiology" OR ta any "interventional radiologist" OR ta any "percutaneous coronary intervention" OR ta any "cardiology")

APPENDIX B: SELECTION OF ARTICLES

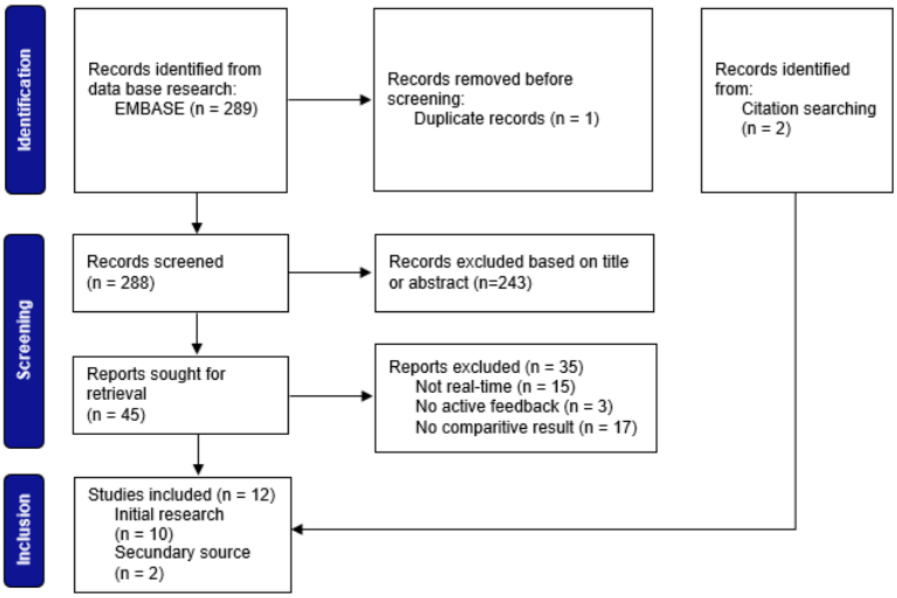


Figure 3: Medbase search: Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA)-diagram of the systematic search[51].

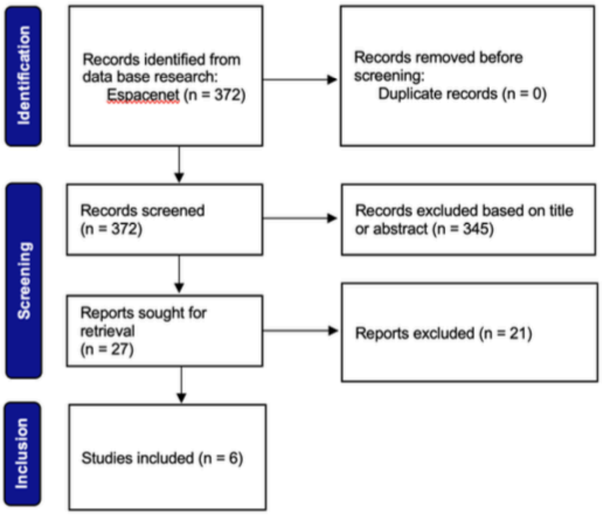


Figure 4: Espacenet search: Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA)-diagram of the systematic search[51].

Appendix B: Measurement set-up

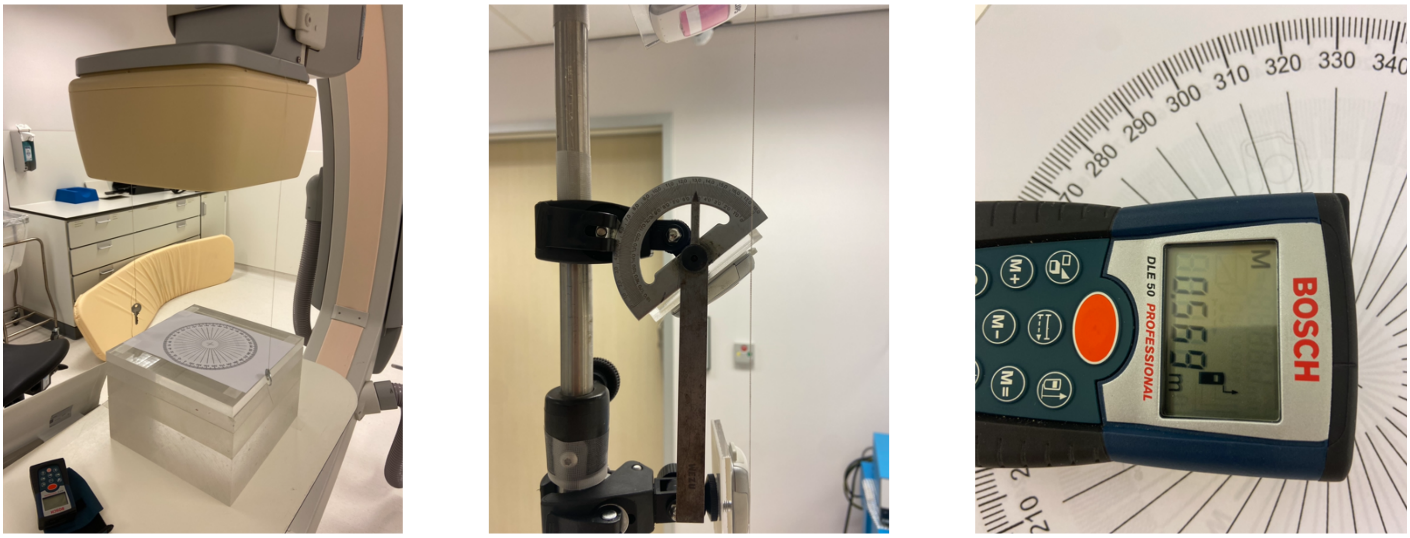


Figure 16: Establishing the correct setup. Left: Alignment of the C-arm with the phantom. Centre: Adjustment of the badge's angle using a weighted string and a protractor. Right: Determination of the pole's orientation and distance in relation to the phantom.

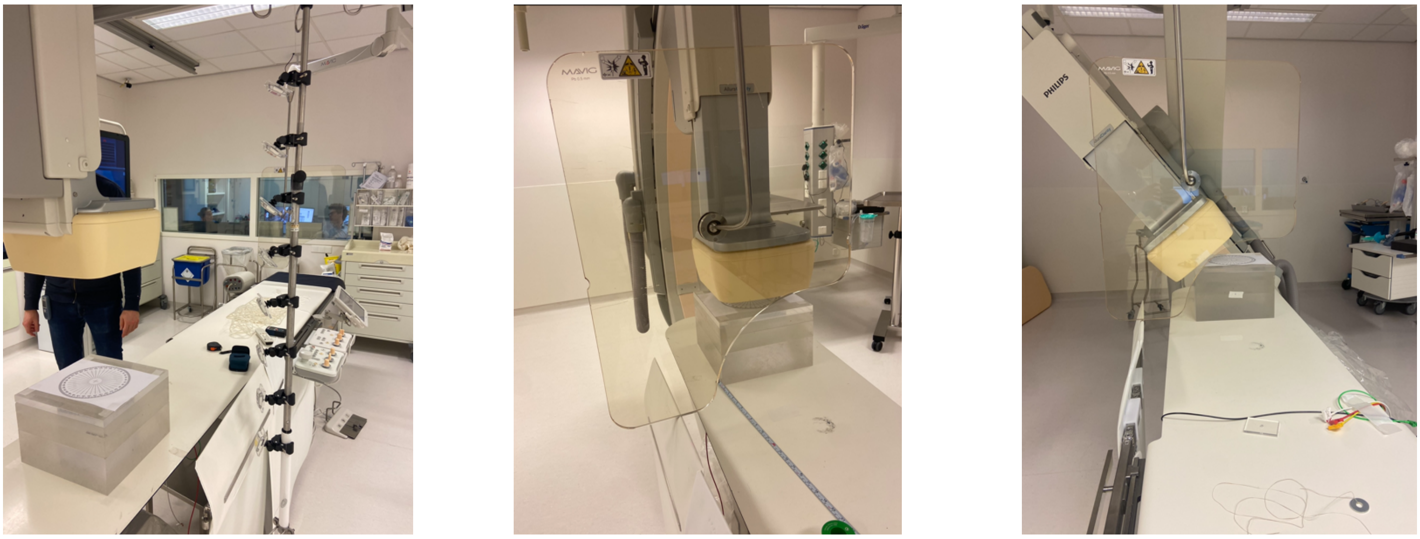


Figure 15: Illustration of the setup. Left: Pole and badges oriented towards the center of the phantom. Middle: The setup with the C-arm in AP view and with the lead screen. Right: The setup with the C-arm in a 40° tilted view and with the lead screen.

Appendix C: Inverse Quadratic Correlation in measurements

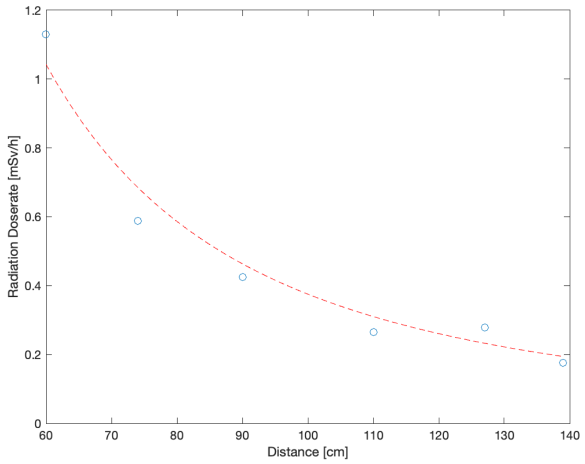


Figure 18: AP orientation C-arm, Acquisition mode, No lead screen (measurements 105 cm above the ground)

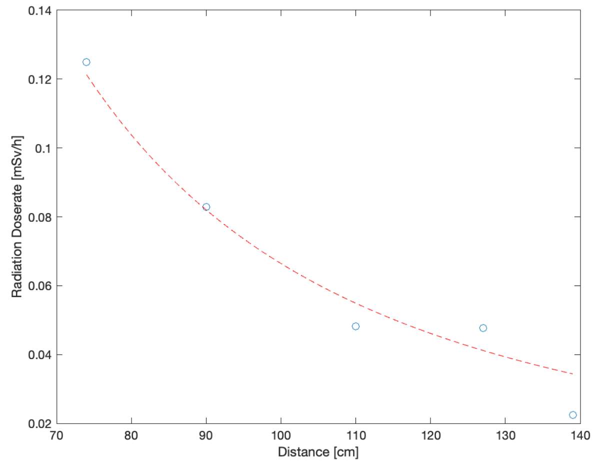


Figure 17: AP orientation C-arm, Fluoroscopy mode, No lead screen (measurements 105 cm above the ground)

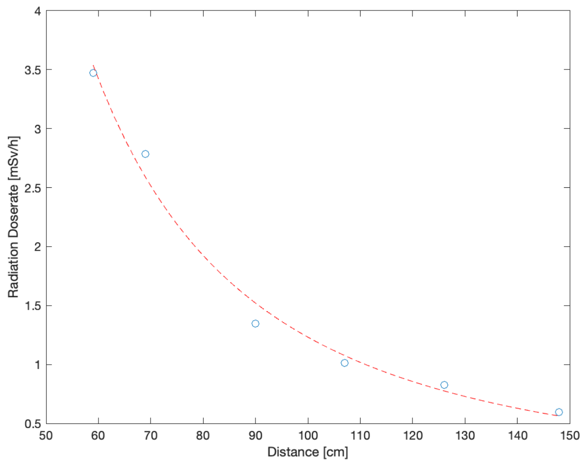


Figure 20: 40° tilted orientation C-arm, Acquisition mode, No lead screen (measurements 105 cm above the ground)

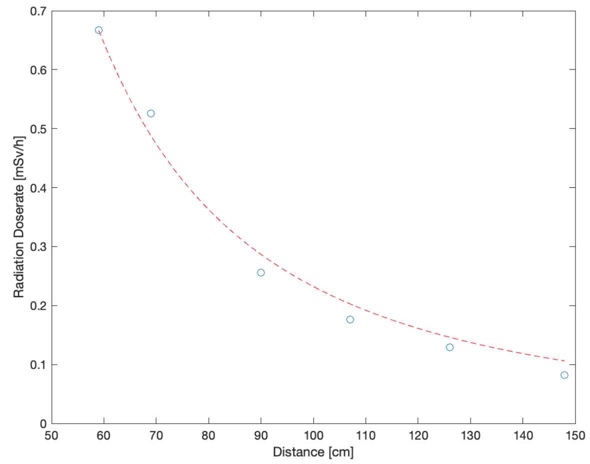


Figure 19: 40° tilted orientation C-arm, Fluoroscopy mode, No lead screen (measurements 105 cm above the ground)

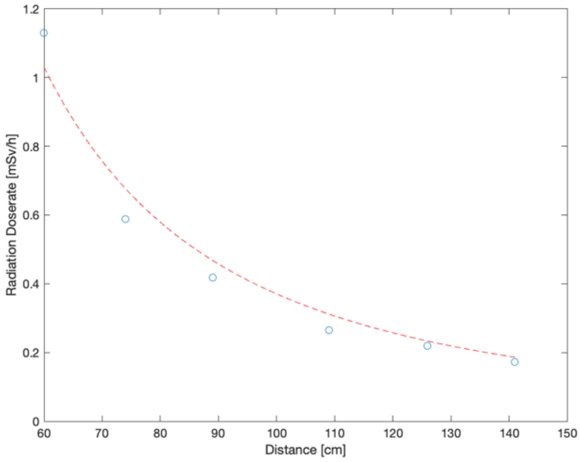


Figure 22: AP orientation C-arm, Acquisition mode, With lead screen (measurements 105 cm above the ground)

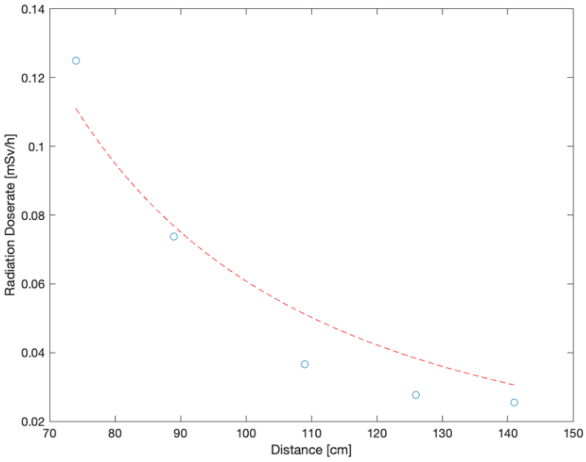


Figure 21: AP orientation C-arm, Fluoroscopy mode, With lead screen (measurements 105 cm above the ground)

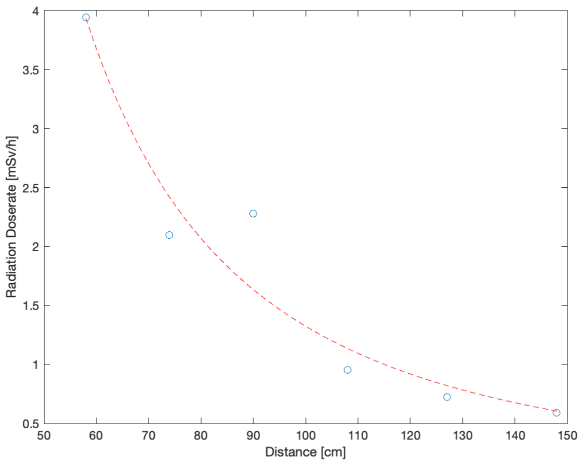


Figure 24: 40° tilted orientation C-arm, Acquisition mode, With lead screen (measurements 105 cm above the ground)

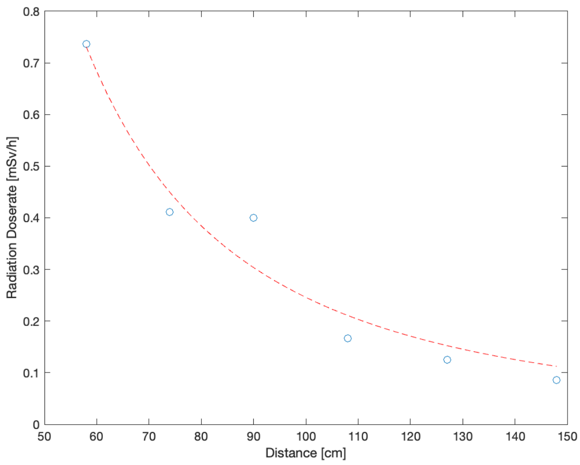


Figure 23: 40° tilted orientation C-arm, Fluoroscopy mode, With lead screen (measurements 105 cm above the ground)

Appendix D: Measurements in points

AP Acquisition

Without lead screen

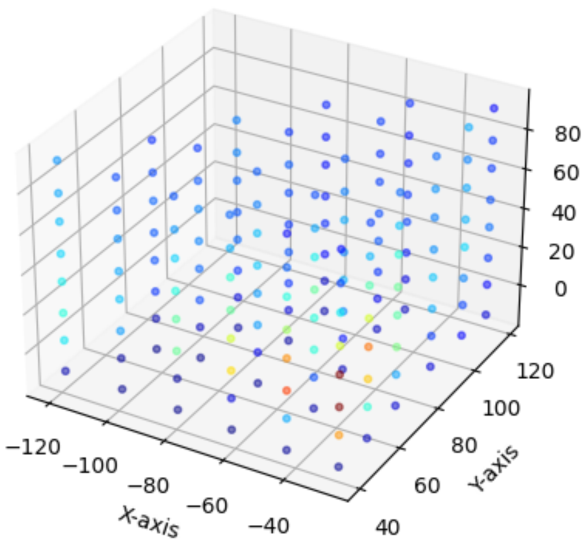


Figure 25: Measurement points; AP orientation, Acquisition mode, Without lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

With lead screen

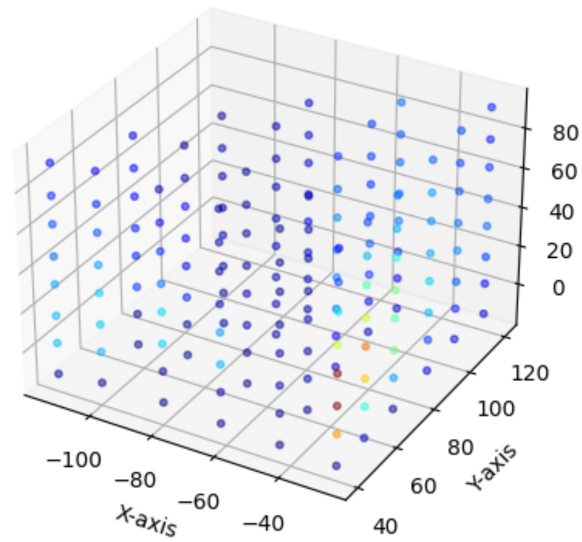


Figure 26: Measurement points; AP orientation, Acquisition mode, With lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

AP Fluoroscopy

Without lead screen

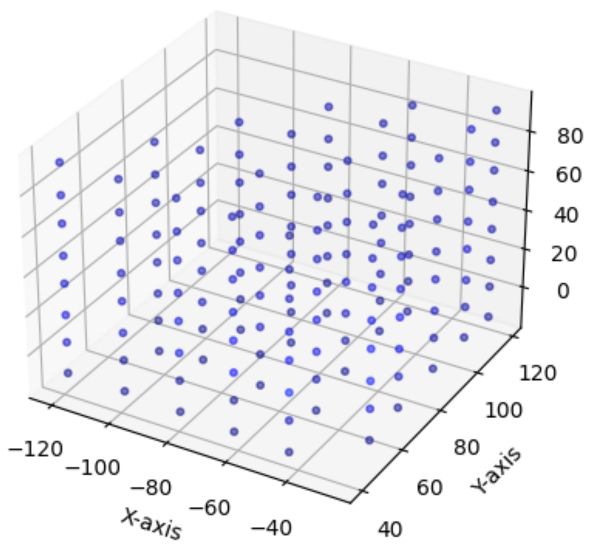


Figure 27: Measurement points; AP orientation, Fluoroscopy mode, Without lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

With lead screen

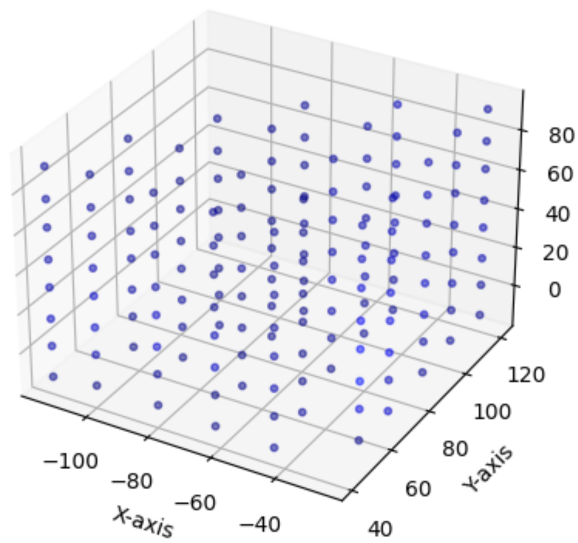


Figure 28: Measurement points; AP orientation, Fluoroscopy mode, With lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

40° Tilt Acquisition

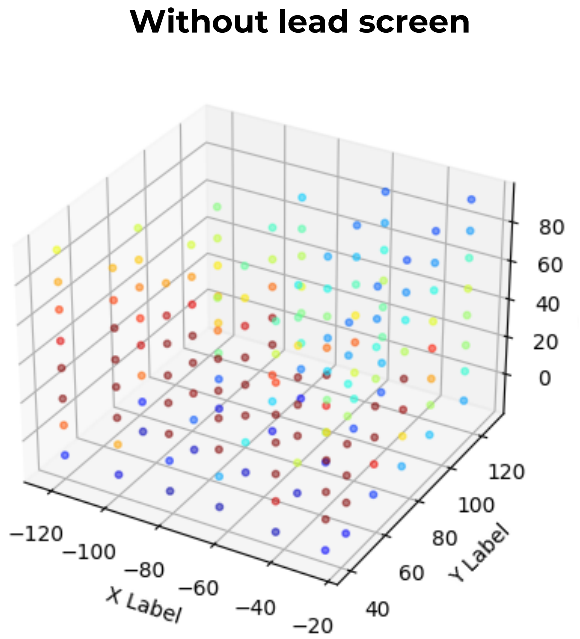


Figure 29: Measurement points; 40° tilted orientation, Acquisition mode, Without lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

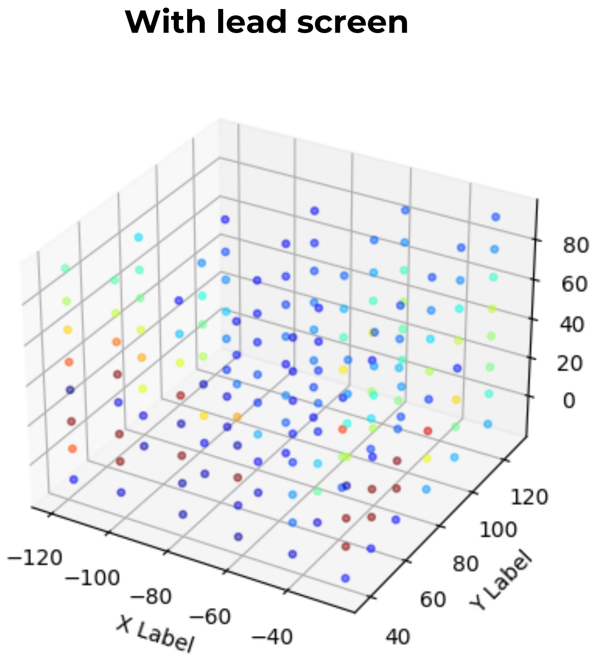


Figure 30: Measurement points; 40° tilted orientation, Acquisition mode, With lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

40° Tilt Fluoroscopy

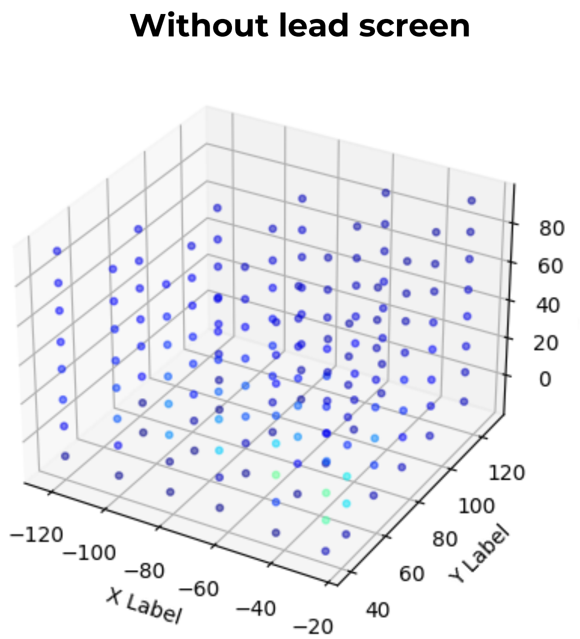


Figure 32: Measurement points; 40° tilted orientation, Fluoroscopy mode, Without lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

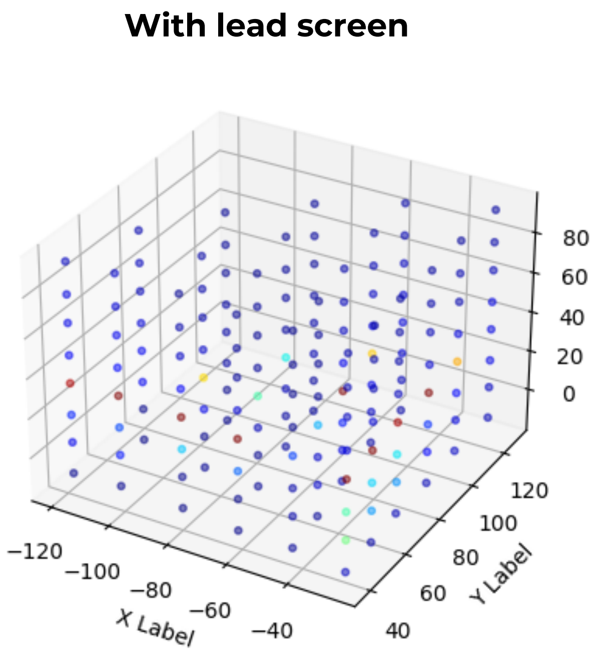


Figure 31: Measurement points; 40° tilted orientation, Fluoroscopy mode, With lead screen. The colour of the dots are dependent on the Doserate value, where dark blue is low and dark red is high.

Appendix E: Interpolated measurement data (Without lead screen)

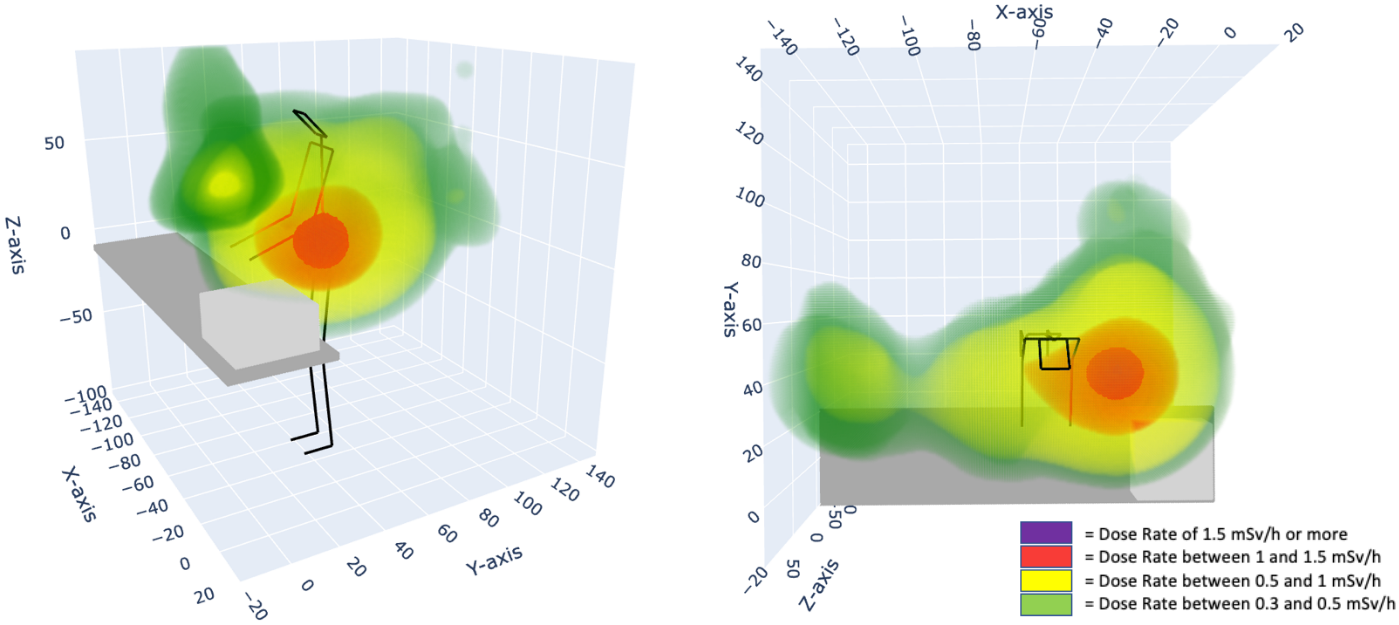


Figure 33: Interpolated visualisation of the data without a lead screen. AP orientation of the C-arm, Acquisition mode

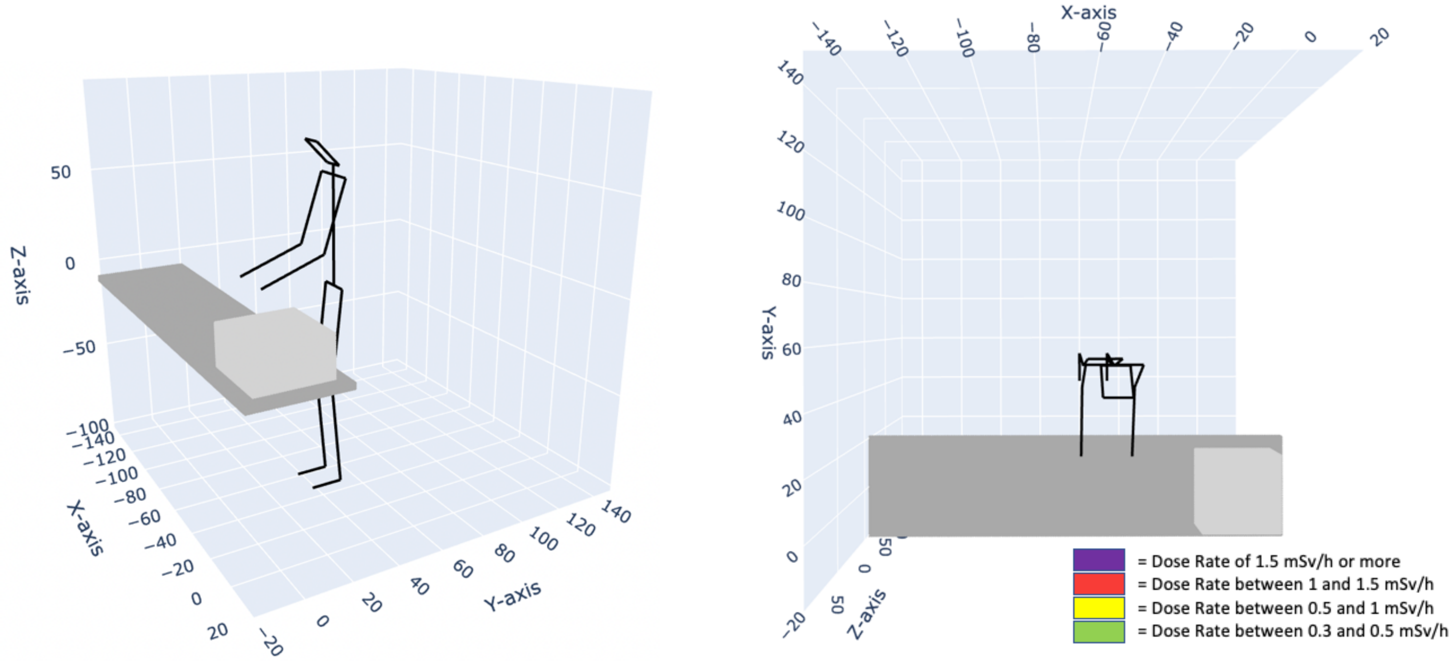


Figure 34: Interpolated visualisation of the data without a lead screen. AP orientation of the C-arm, Fluoroscopy mode

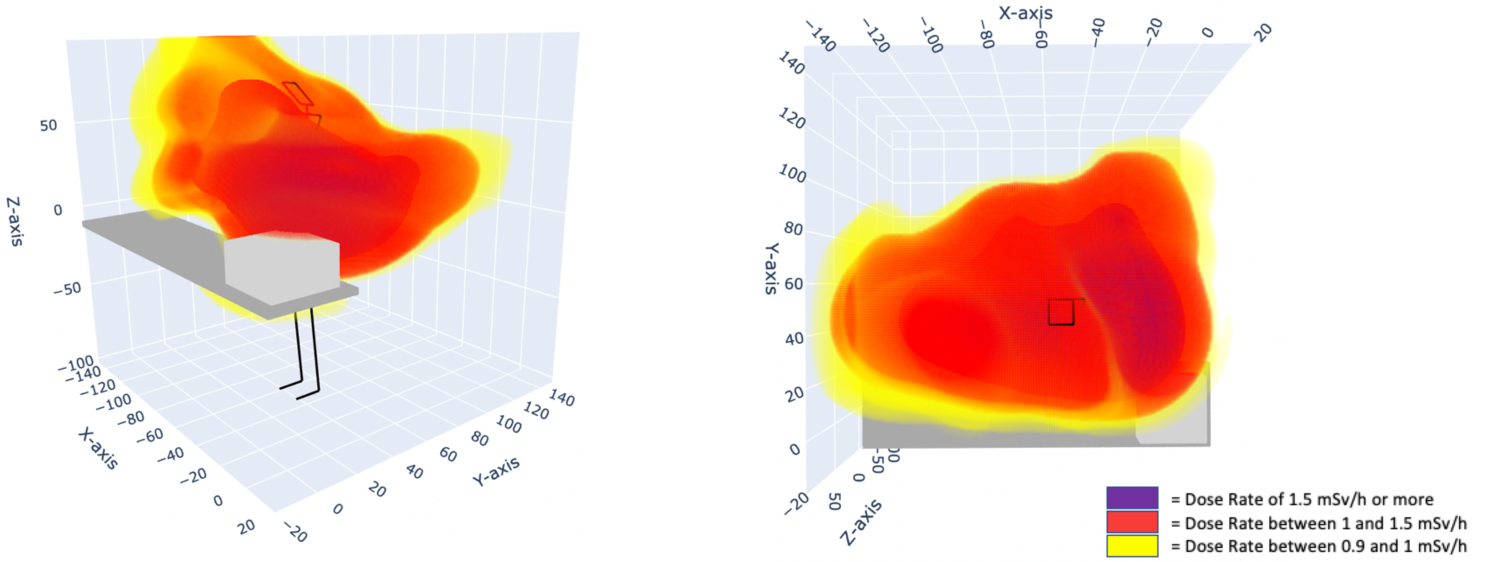


Figure 36: Interpolated visualisation of the data without a lead screen. 40° tilted orientation of the C-arm, Acquisition mode

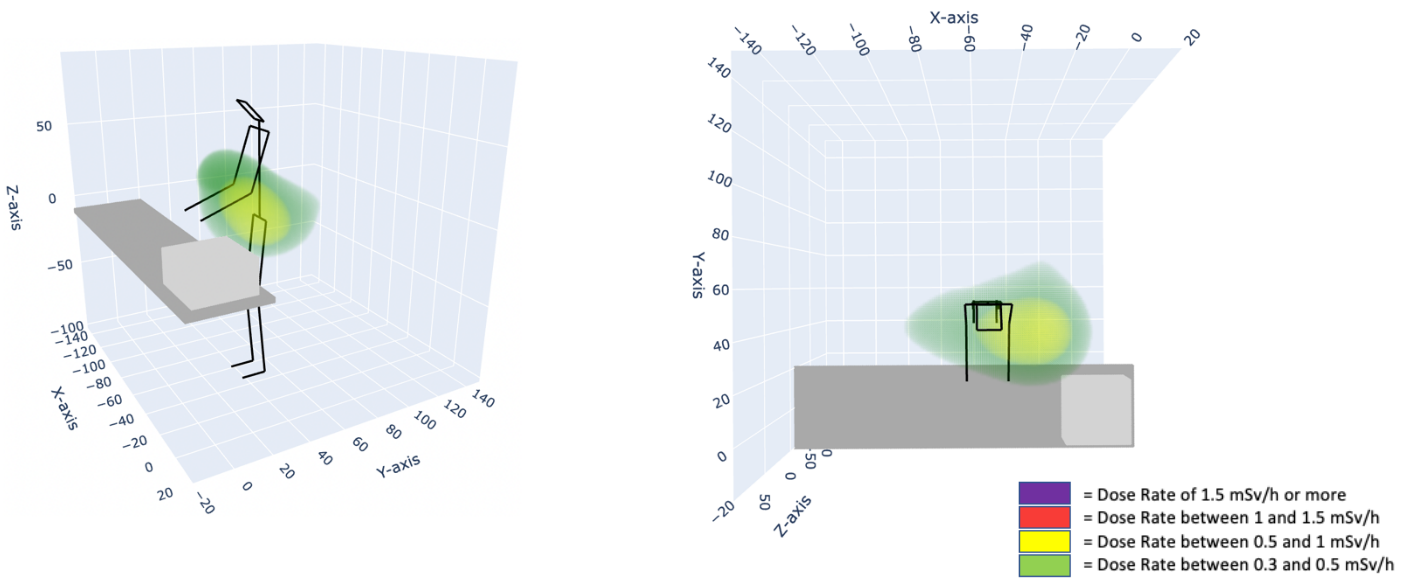


Figure 35: Interpolated visualisation of the data without a lead screen. 40° tilted orientation of the C-arm, Fluoroscopy mode

Appendix F: Interpolated measurement data (With lead screen)

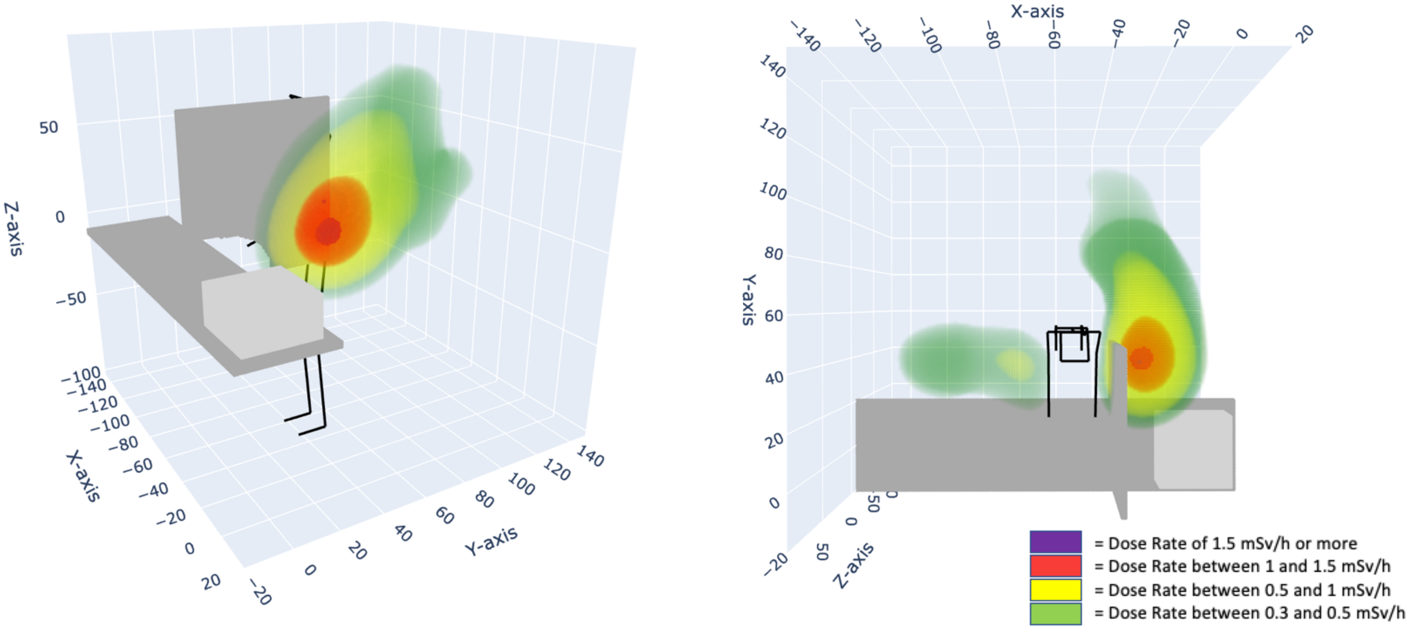


Figure 37: Interpolated visualisation of the data with a lead screen. AP orientation of the C-arm, Acquisition mode

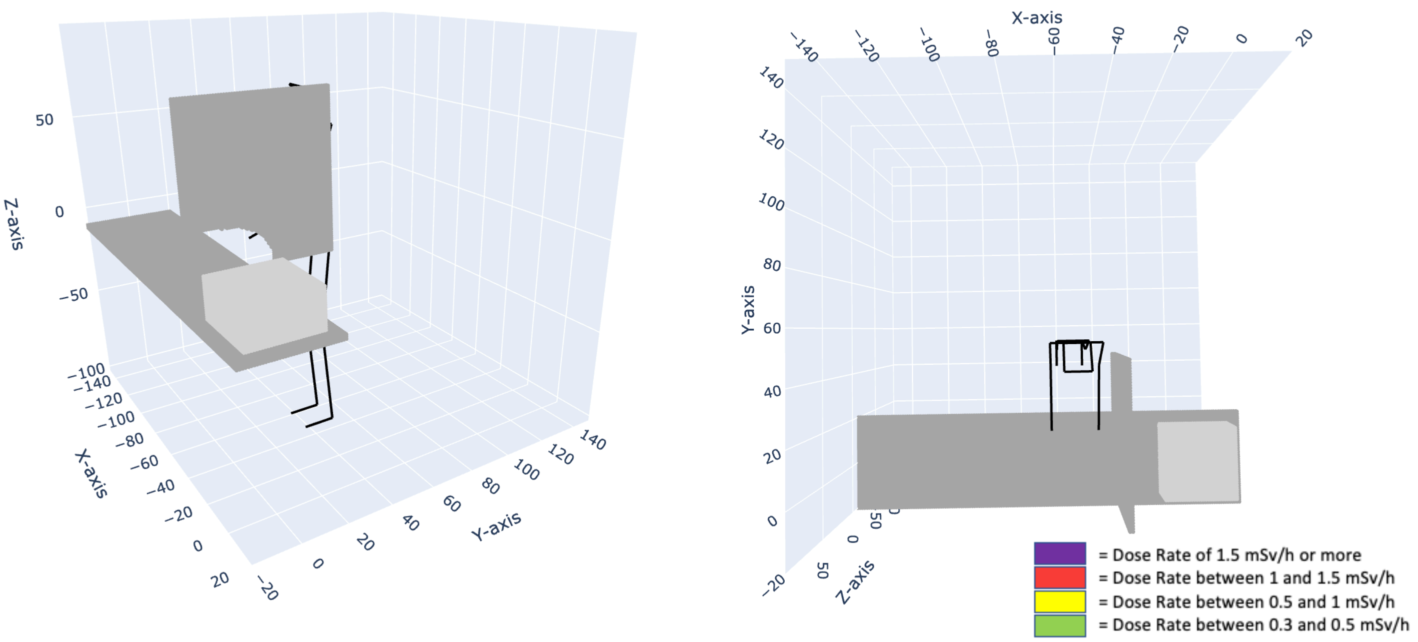


Figure 38: Interpolated visualisation of the data with a lead screen. AP orientation of the C-arm, Fluoroscopy mode

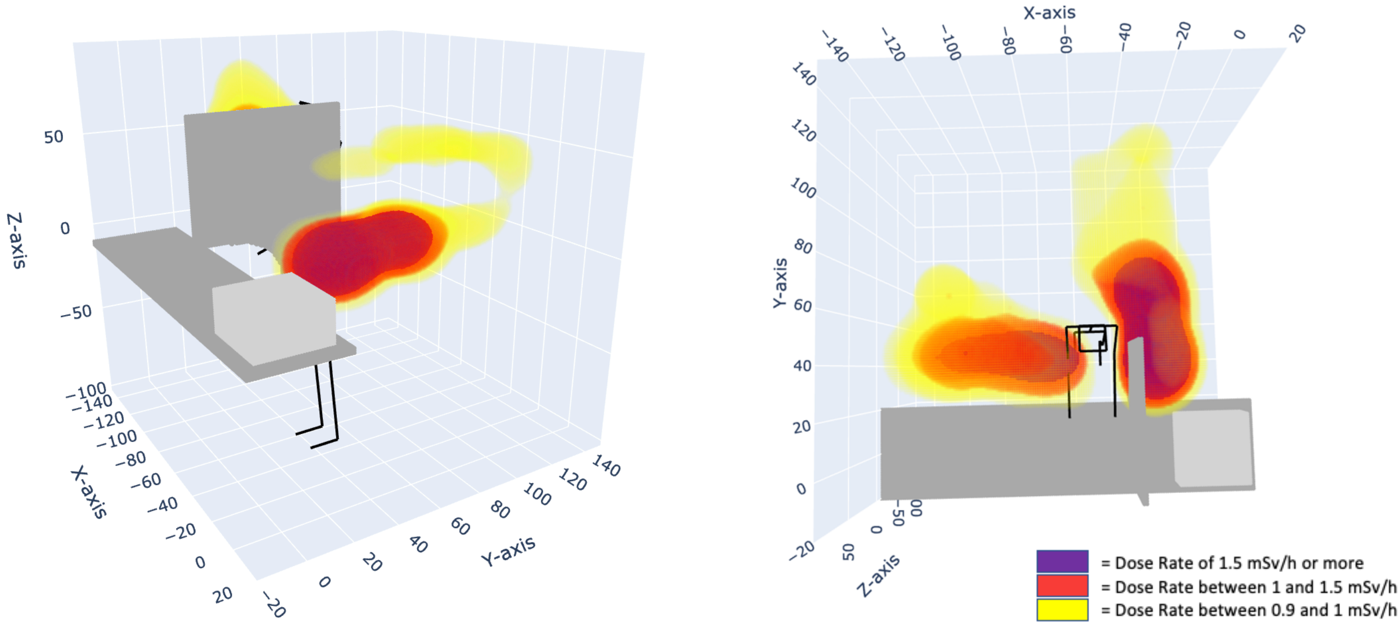


Figure 39: Interpolated visualisation of the data with a lead screen. 40° tilted orientation of the C-arm, Acquisition mode

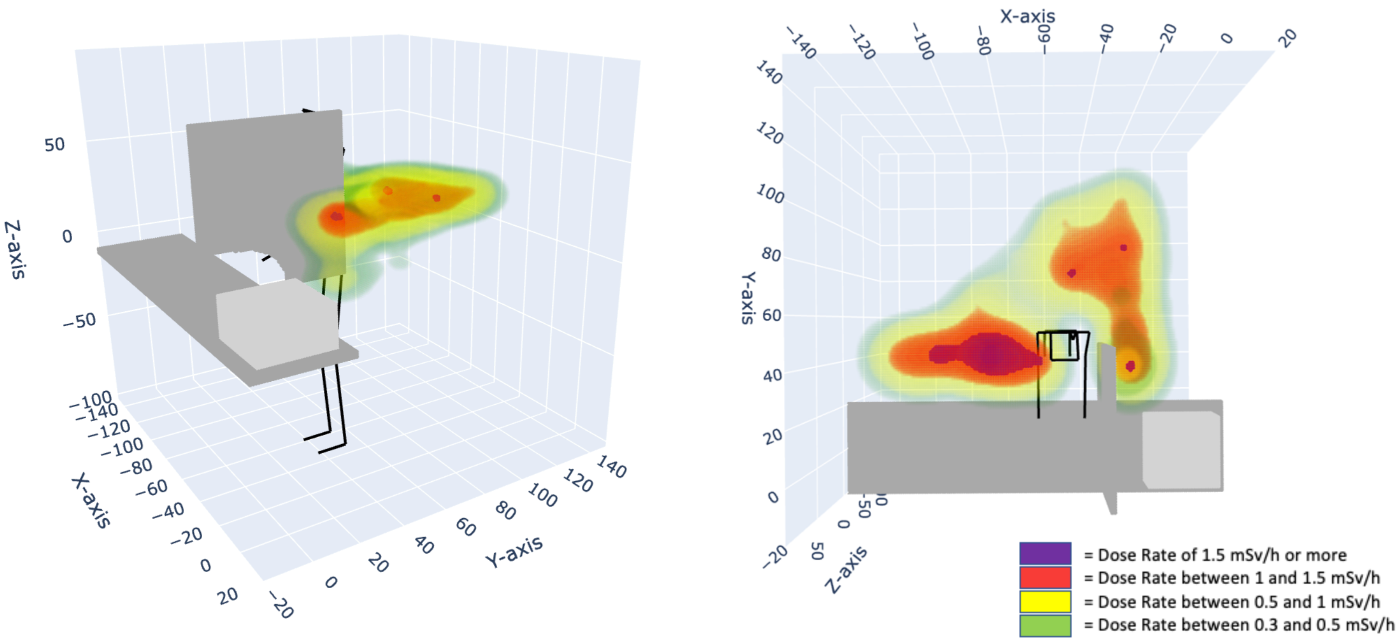


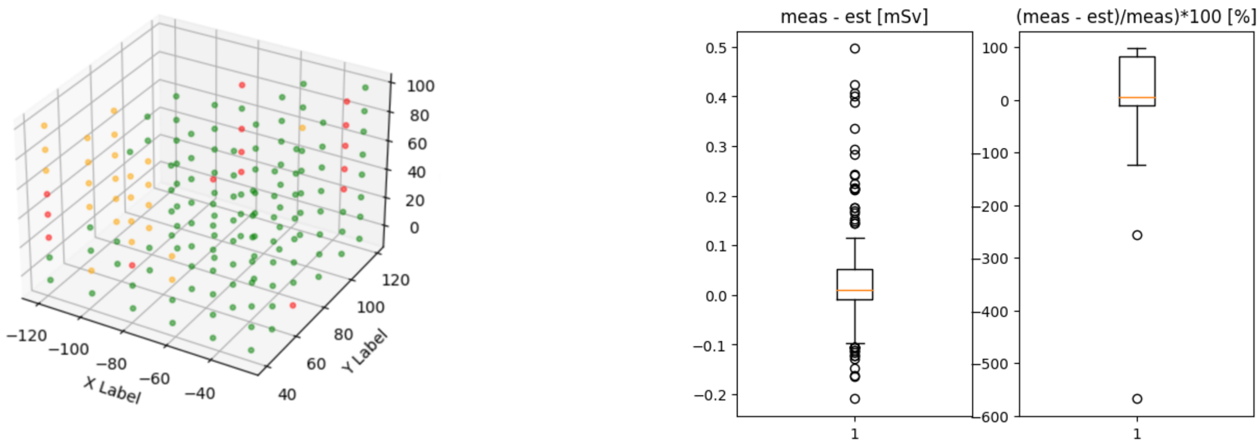
Figure 40: Interpolated visualisation of the data with a lead screen. 40° tilted orientation of the C-arm, Fluoroscopy mode

Appendix G: Deviation Estimation & Measurement

Acquisition AP (Total points: 168)

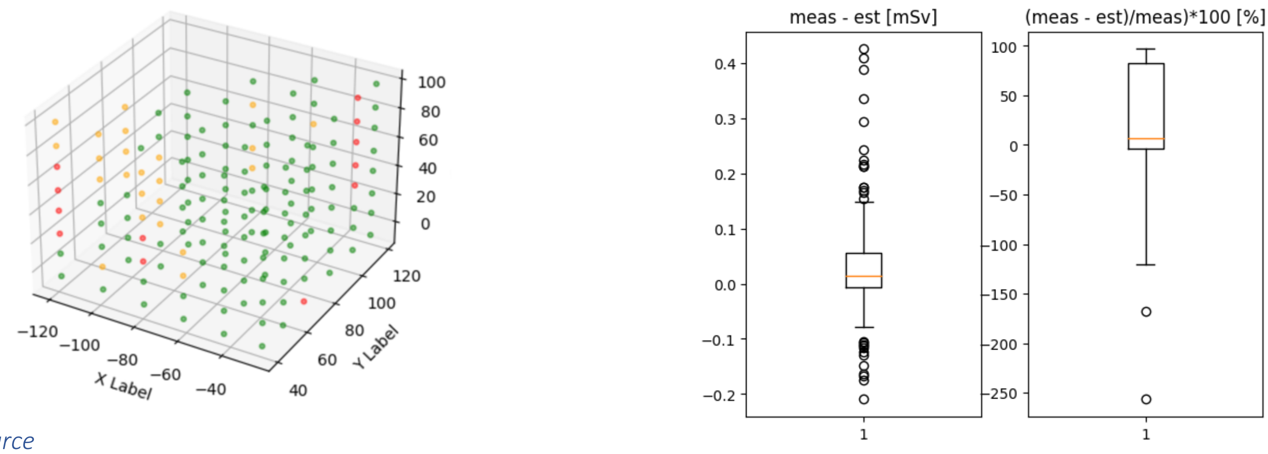
Point Centre of the source

Estimation gives higher dose rate than measurement: 15 (Red)
Estimation correct (within 0.1 mSv/h deviation): 128 (Green)
Estimation gives lower dose rate than measurement: 25 (Orange)



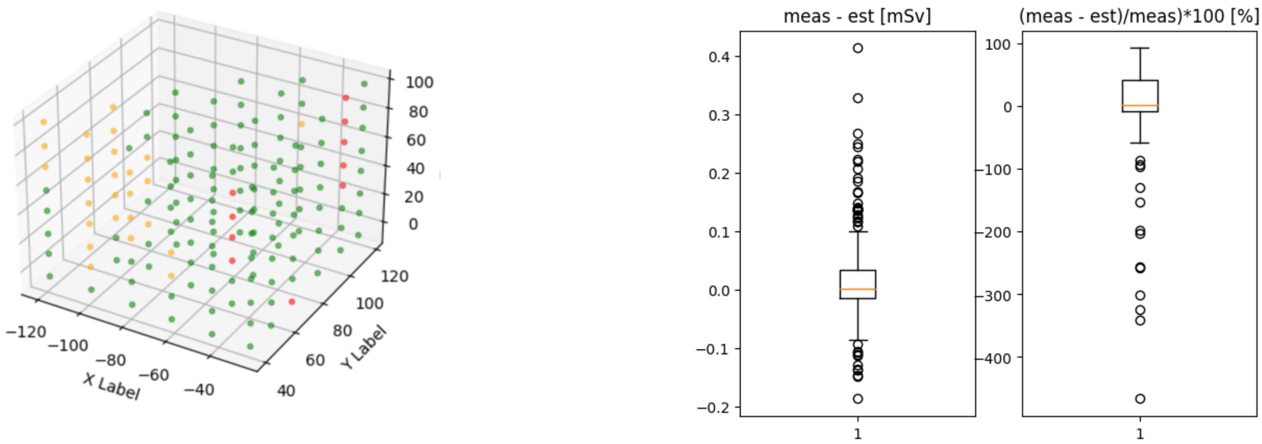
Point Low in the source

Estimation gives higher dose rate than measurement: 12 (Red)
Estimation correct: 133 (Green)
Estimation gives lower dose rate than measurement: 23 (Orange)



3D Source

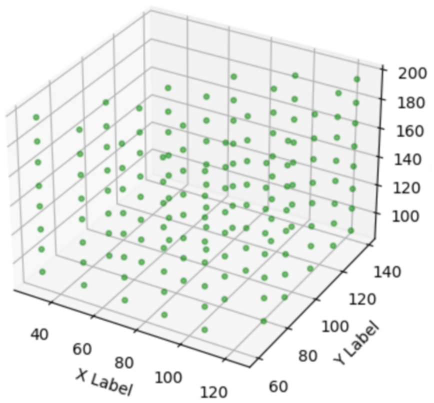
Estimation gives higher dose rate than measurement: 10 (Red)
Estimation correct: 132 (Green)
Estimation gives lower dose rate than measurement: 26 (Orange)

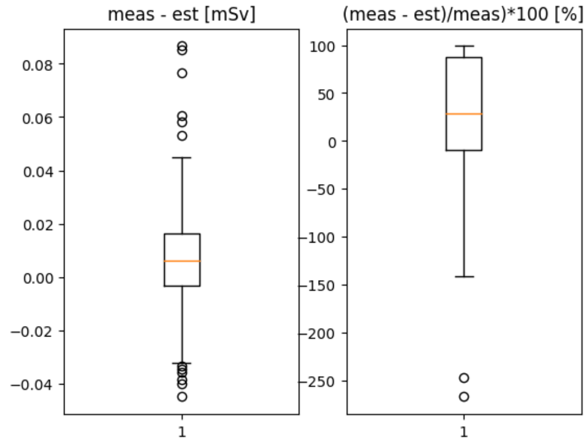


Fluoroscopy AP (Total points: 160)

Point Centre of the source

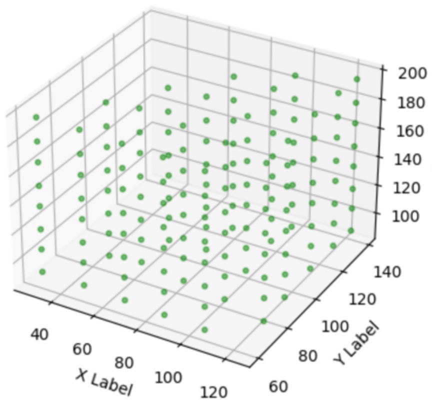
Estimation gives higher dose rate than measurement: 0 (Red)
Estimation correct: 160 (Green)
Estimation gives lower dose rate than measurement: 0 (Orange)

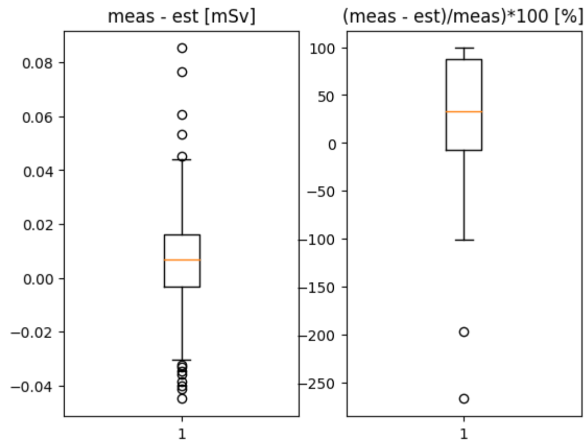




Point Low in the source

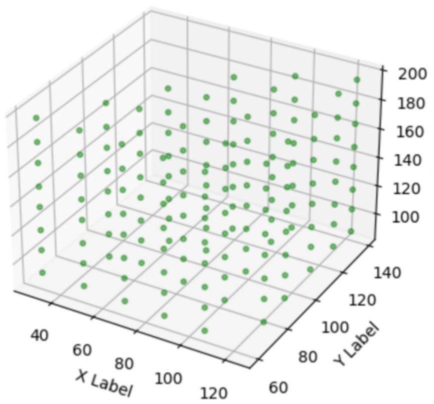
Estimation gives higher dose rate than measurement: 0 (Red)
Estimation correct: 160 (Green)
Estimation gives lower dose rate than measurement: 0 (Orange)

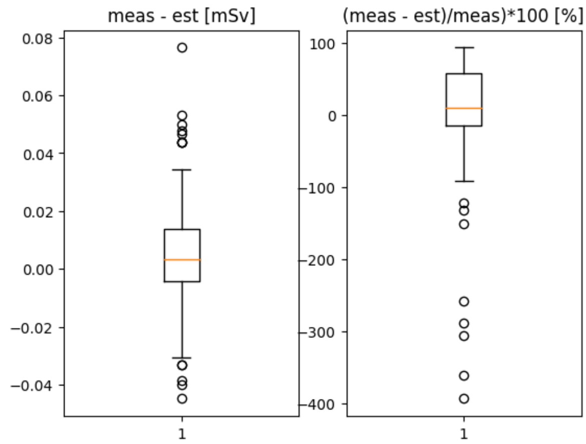




3D Source

Estimation gives higher dose rate than measurement: 0 (Red)
Estimation correct: 160 (Green)
Estimation gives lower dose rate than measurement: 0 (Orange)

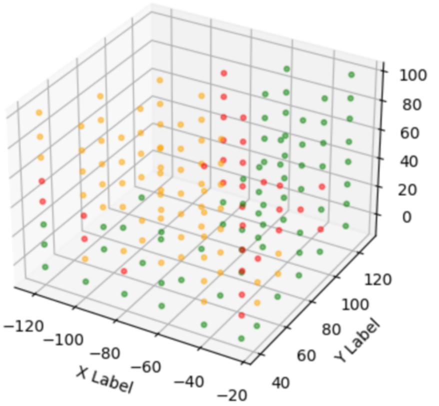


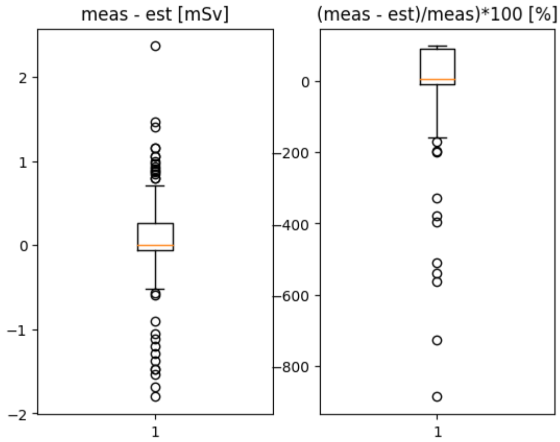


Acquisition 40° tilt

Point Centre of the source

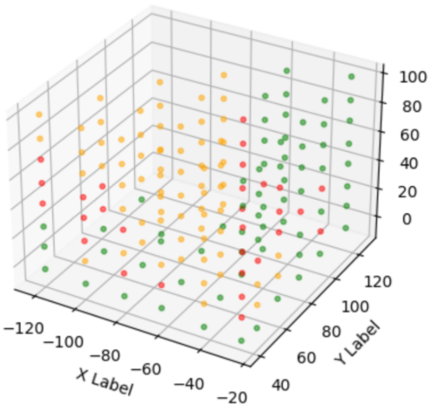
Estimation gives higher dose rate than measurement: 30 (Red)
Estimation correct: 70 (Green)
Estimation gives lower dose rate than measurement: 68 (Orange)

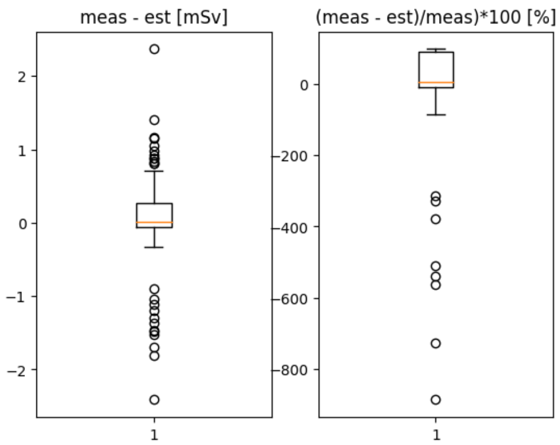




Point Low in the source

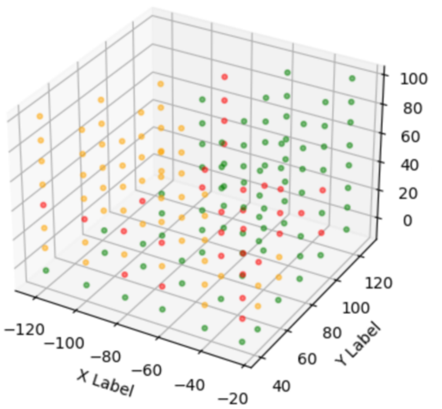
Estimation gives higher dose rate than measurement: 29 (Red)
Estimation correct: 67 (Green)
Estimation gives lower dose rate than measurement: 72 (Orange)

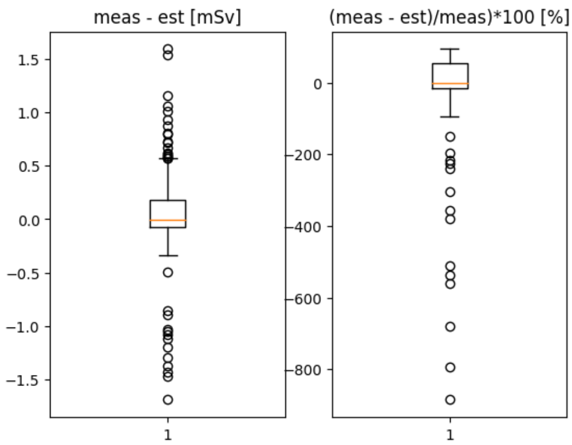




3D Source

Estimation gives higher dose rate than measurement: 31 (Red)
Estimation correct: 82 (Green)
Estimation gives lower dose rate than measurement: 55 (Orange)

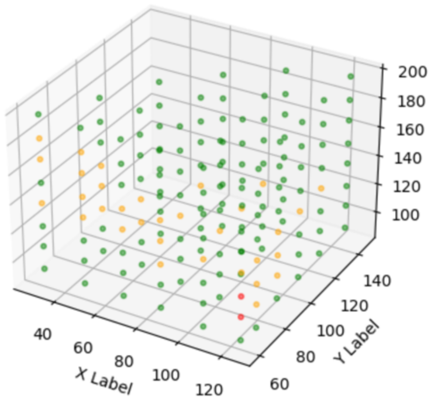


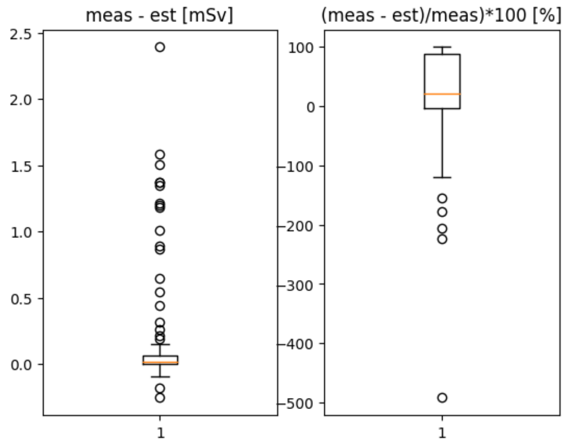


Fluoroscopy 40° tilt

Point Centre of the source

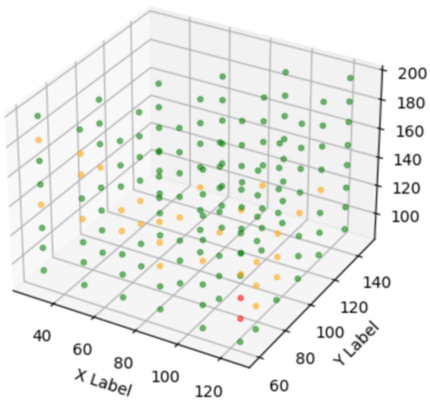
Estimation gives higher dose rate than measurement: 2 (Red)
Estimation correct: 134 (Green)
Estimation gives lower dose rate than measurement: 32 (Orange)

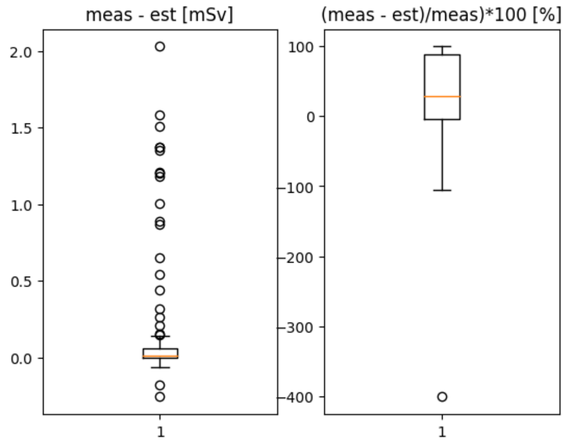




Point Low in the source

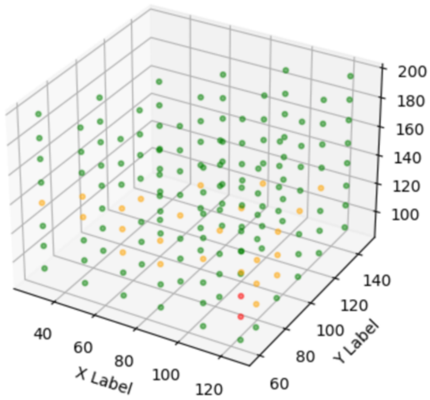
Estimation gives higher dose rate than measurement: 2 (Red)
Estimation correct: 138 (Green)
Estimation gives lower dose rate than measurement: 28 (Orange)

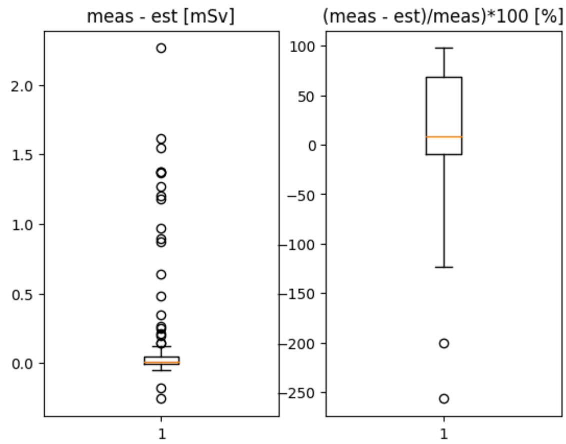




3D Source

Estimation gives higher dose rate than measurement: 2 (Red)
Estimation correct: 142 (Green)
Estimation gives lower dose rate than measurement: 24 (Orange)





Appendix H: Visualisation of difference measurement and estimation

Acquisition AP

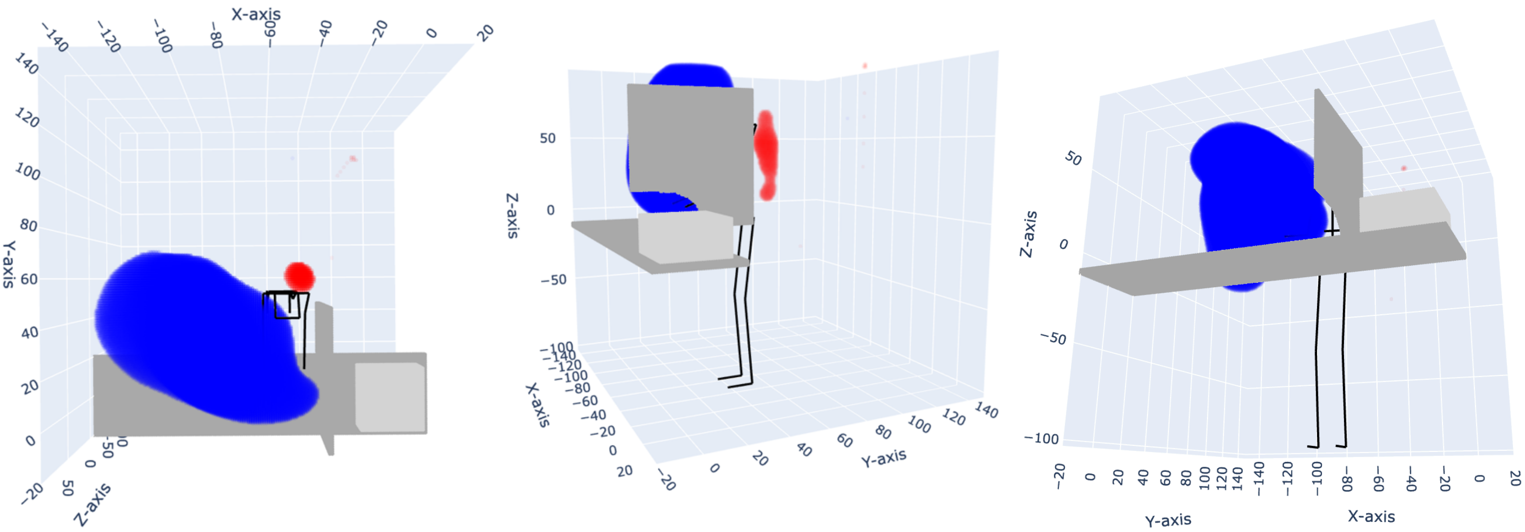


Figure 41: Interpolated visualisation of the inaccurately estimated values. AP orientation of C-arm, Acquisition mode. Blue areas represent instances where the estimation provided a dose rate of at least 0.1 mSv/h lower compared to the measurements, indicating that the model overestimated the amount of radiation blocked. Conversely, red areas signify cases where the estimation yielded a dose rate of at least 0.1 mSv/h higher compared to the measurements.

Fluoroscopy AP

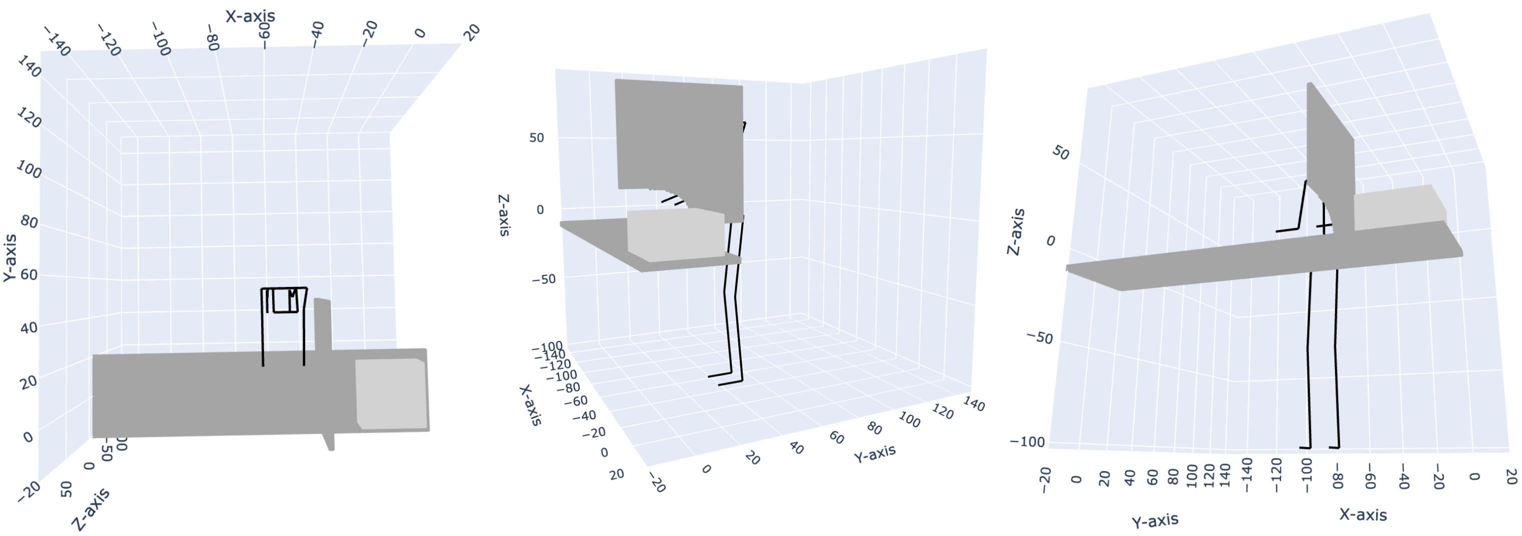


Figure 42: Interpolated visualisation of the inaccurately estimated values. AP orientation of C-arm, Fluoroscopy mode. Blue areas represent instances where the estimation provided a dose rate of at least 0.1 mSv/h lower compared to the measurements, indicating that the model overestimated the amount of radiation blocked. Conversely, red areas signify cases where the estimation yielded a dose rate of at least 0.1 mSv/h higher compared to the measurements.

Acquisition 40° Tilt

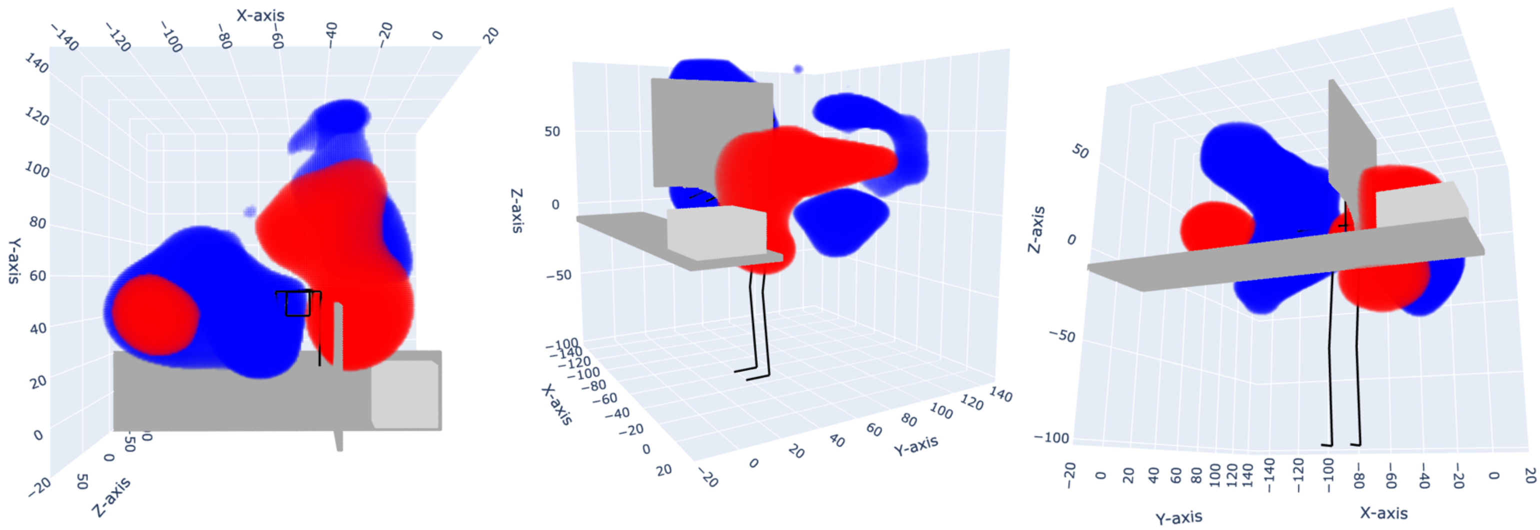


Figure 43: Interpolated visualisation of the inaccurately estimated values. 40° tilted orientation of C-arm, Acquisition mode. Blue areas represent instances where the estimation provided a dose rate of at least 0.1 mSv/h lower compared to the measurements, indicating that the model overestimated the amount of radiation blocked. Conversely, red areas signify cases where the estimation yielded a dose rate of at least 0.1 mSv/h higher compared to the measurements.

Fluoroscopy 40° Tilt

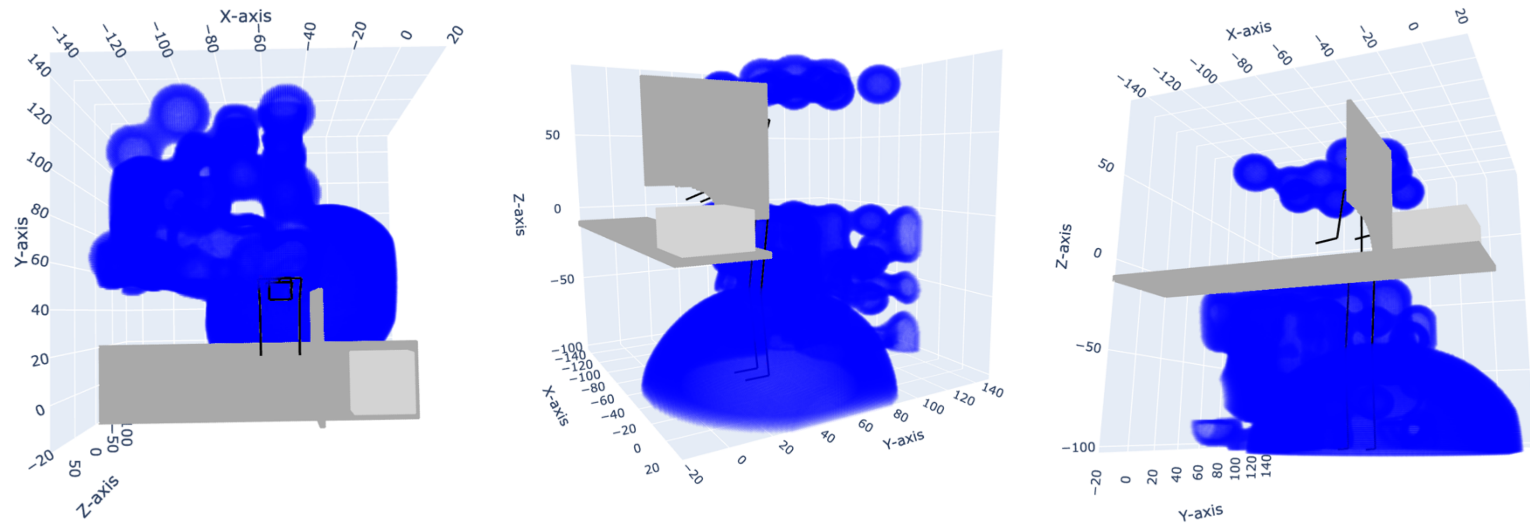


Figure 44: Interpolated visualisation of the inaccurately estimated values. 40° tilted orientation of C-arm, Fluoroscopy mode. Blue areas represent instances where the estimation provided a dose rate of at least 0.1 mSv/h lower compared to the measurements, indicating that the model overestimated the amount of radiation blocked. Conversely, red areas signify cases where the estimation yielded a dose rate of at least 0.1 mSv/h higher compared to the measurements.

Appendix I: Interpolated data with lead screen (Three positions)

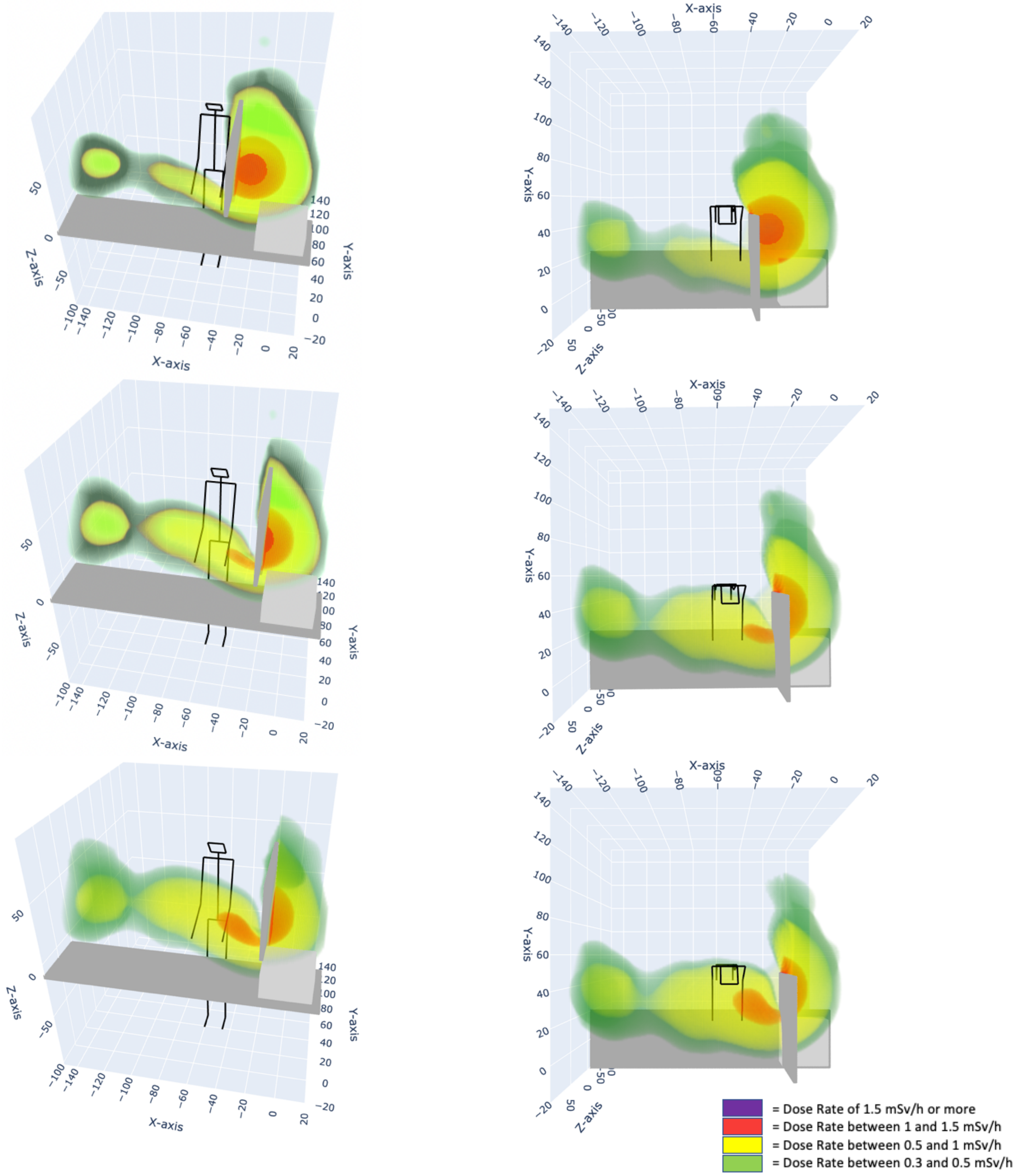


Figure 45: Estimated scatter patterns for three different lead screen positions with an AP orientation of the C-arm. Top: Lead screen positioned 20 cm from the edge of the phantom. Middle: Lead screen positioned 5 cm from the edge of the phantom. Bottom: Lead screen positioned 0 cm from the edge of the phantom.

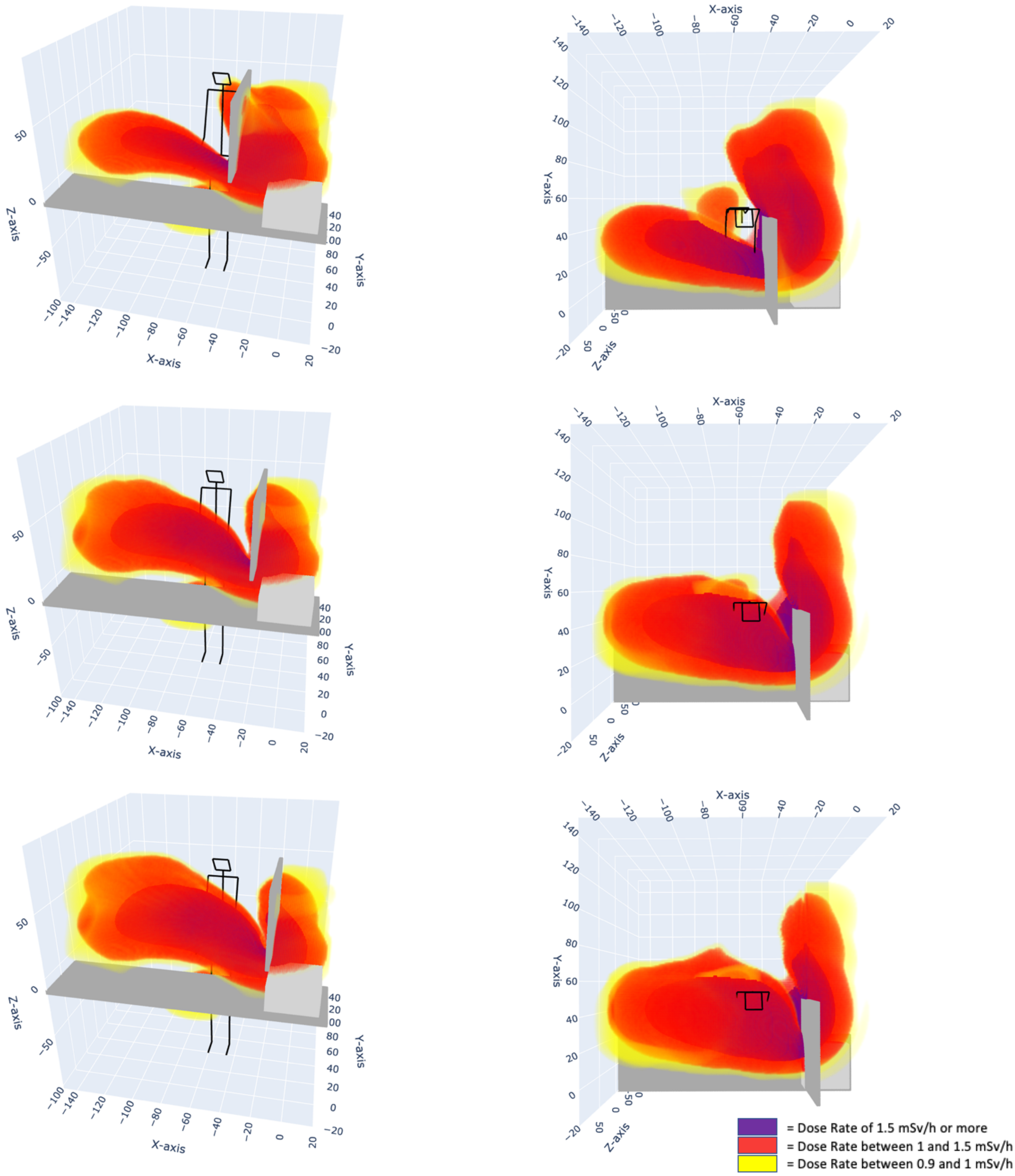


Figure 46: Estimated scatter patterns for three different lead screen positions with a 40° tilted orientation of the C-arm. Top: Lead screen positioned 20 cm from the edge of the phantom. Middle: Lead screen positioned 5 cm from the edge of the phantom. Bottom: Lead screen positioned 0 cm from the edge of the phantom.

Appendix J: Dose Rate Clinicians for different positions lead screen

Interventional Cardiologist	Location	Dose rate without shield [mSv/h]	Dose rate with shield on spot measurement (20 cm to phantom) [mSv/h]	Dose rate with shield closer to phantom (5 cm to phantom) [mSv/h]	Dose rate with shield next to phantom (0 cm to phantom) [mSv/h]
Acquisition mode AP orientation	Chest	0.680	0.018	0.461	0.574
	Head	0.349	0.009	0.114	0.183
Fluoroscopy mode AP orientation	Chest	0.101	0.003	0.068	0.085
	Head	0.057	0.001	0.019	0.030
Acquisition mode 40° tilt	Chest	1.556	0.041	1.054	1.313
	Head	1.023	0.026	0.334	0.537
Fluoroscopy mode 40° tilt	Chest	0.237	0.006	0.160	0.200
	Head	0.157	0.004	0.051	0.082
Percentage of dose rate without shield	Chest	-	2.6%	67.7%	84.4%
	Head	-	2.6%	32.7%	52.5%

Table 4: Estimate dose rates for the Interventional Cardiologist on the chest and the head for three different positions of the lead screen

Assistant / scrub nurse	Location	Dose rate without shield [mSv/h]	Dose rate with shield on spot measurement (20 cm to phantom) [mSv/h]	Dose rate with shield closer to phantom (5 cm to phantom) [mSv/h]	Dose rate with shield next to phantom (0 cm to phantom) [mSv/h]
Acquisition mode AP orientation	Chest	0.417	0.399	0.413	0.415
	Head	0.376	0.258	0.347	0.362
Fluoroscopy mode AP orientation	Chest	0.075	0.072	0.074	0.075
	Head	0.066	0.045	0.060	0.063
Acquisition mode 40° tilt	Chest	0.938	0.899	0.931	0.935
	Head	0.927	0.635	0.855	0.892
Fluoroscopy mode 40° tilt	Chest	0.145	0.139	0.143	0.144
	Head	0.140	0.096	0.130	0.135
Percentage of measurement with no shield	Chest	-	95.8%	99.2%	99.6%
	Head	-	68.5%	92.3%	96.3%

Table 5: Estimate dose rates for the Assistant / Scrub nurse on the chest and the head for three different positions of the lead screen

Appendix K: Questionnaire Interventional Cardiologists

	Interventional Cardiologist 1	Interventional Cardiologist 2	Interventional Cardiologist 3	Interventional Cardiologist 4	Interventional Cardiologist 5
Current radiation safety					
Importance of radiation safety during a procedure (1-10)	8	9	4	8	9
Level of concern on experiencing negative impacts from radiation exposure (1-10)	3	8	3	4	1
Consistency of wearing protective lead apron and collar (never, sometimes, often, always)	Always	Always	Always	Always	Always
Consistency of wearing protective lead glasses (never, sometimes, often, always)	Never	Always	Never	Sometimes	Never
Number of times changing position of lead screen during Coronary Angiogram procedure and why?	5 times → inconvenient position for procedure	2 times → better connection to the patient	4 times → Is in the way of C-arm or entry in patient.	3 times → It collides with the C-arm	For every position of the C-arm → Provides better protection
Indication of location to use for the positioning of the lead screen	Heart of the patient, lead screen close to entry radiation without getting in the primary beam	Centre of patient in radiation area, the shield close towards the C-arm.	The heart of the patient	As close as possible to centre of radiation area to block as much as possible, also for the assistant	The source of the C-arm
Challenges of positioning of the lead screen	Difficult to know what the best placement is	-	Is often in the way.	Is difficult that it's a hard shape instead of something adjustable	Difficult that it's rigid and hard to move with the arm on the ceiling
Factors that are considered during a procedure to reduce radiation exposure	As short as possible and low frame rate	Short recordings, diaphragming, detector close to patient → Patient most important	No orientating recordings and short recordings	No considerations, procedure and patient come on the first place	Patient and diagnostics are most important, so no considerations

	Interventional Cardiologist 1	Interventional Cardiologist 2	Interventional Cardiologist 3	Interventional Cardiologist 4	Interventional Cardiologist 5
Radiation Feedback					
Frequency of received feedback on radiation exposure	Once a month → real-time would be better	4 times a year → I don't look at it, as it won't change the way I'm operating	Monthly, but looks at it maybe once a year	Monthly, but is already a done deal, so I don't look at it	Monthly, but I look at briefly twice a year
Perception of received radiation exposure (to high, acceptable, good)	Acceptable	Acceptable	Good, not concerned with radiation	Acceptable	Acceptable
Opinion on the effectiveness of using the following methods as a feedback method					
Bar graph	7	8	7	6.5	8
Sounds	3	3	1	1	2
Wearable	5	3	1	5	2
Augmented Reality (glasses)	3	5	6	8	2
Augmented Reality (Projection on the floor)	7	6.5	7	8	4
Augmented Reality (Projection on the ceiling)	5	5	1	2	4
Augmented Reality (visualisation on monitor)	7	8	8	7	7
Advice on optimal position lead screen (on lead screen)	9	8.5	7.5	9	9
Advice on optimal position lead screen (on monitor)	8	6	8	5	8
Optimal feedback solution for radiation safety	Better training, so more understanding of how to implement the right measures	Combination of AR with screen impact on screen would be optimal, also for the assistants	Expert that sometimes comes along to explain it	Want to get feedback if I do something suboptimal, also in comparison to colleagues	Robot which optimises place of lead screen