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# Visualizing X-ray radiation levels with the Microsoft HoloLens

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# Abstract

The ALARA principle (As Low As Reasonably Achievable) encourages hospitals to keeping radiation doses for staff and patients as low as possible. Fluoroscopy not only exposes the patient to radiation, but also the specialist and other personnel in the room. We developed a HoloLens application to simulate and visualize scatter radiation levels during a fluoroscopy procedure in an operating room. We use holograms to improve the understanding of interventional cardiologists, - radiologists, and technologists of radiation patterns and to support them in identifying positions with high and low radiation levels. Medical physicists evaluated the application and deemed the physics model adequate for this application and agreed with the methods that were used. Additionally, we conducted a first series of user tests on the prototype HoloLens application in the radiology and cardiology departments of the Albert Schweitzer hospital to assess the effect of the visualization. Our results cannot statistically confirm that users experience a learning effect, but do indicate that participants perform better at identifying unsafe positions inside the operating room. Our research concludes that mixed reality shows promise for radiation safety training purposes in hospitals and therefore deserves further research and development.

# Acknowledgements

Some amazing people have supported me during this project, so I would like to express my gratitude to them.

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# Chapter 1

# Introduction

The Albert Schweitzer hospital in Dordrecht in the Netherlands, is one of many hospitals that conduct operations using Röntgen radiation (also called X-radiation). X-radiation allows specialists to look "inside" the human body, without having to make an incision. More complex operations require the use of fluoroscopy. Fluoroscopy can be described as a movie of X-ray images during an operation. This "movie" is displayed on a monitor hanging above the patient, so the specialist can view it while operating. However fluoroscopy requires large doses of radiation. It not only exposes the patient to radiation, but also the specialist and other staff in the room [1]–[5]. The ALARA principle (As Low As Reasonably Achievable) encourages hospitals to keeping radiation doses for staff and patients as low as possible [6], [7].

In 2015 the interventional cardiologists in the Albert Schweitzer hospital were on average exposed to 15 to 20 millisievert (mSv). This is below the recommendation of the International Commission on Radiological Protection (ICRP) [8] and International Atomic Energy Agency (IAEA) [9]. Even though the radiation dosage was below the recommended limit, staff from the interventional radiology and cardiology department of the Albert Schweitzer hospital expressed their concerns about radiation exposure. Not being able to see radiation patterns made them question the optimal position they should occupy during procedures. The optimal position is where the radiation exposure is as low as reasonably achievable. A two-dimensional image of the radiation patterns in the operating room created by the hospital helped to get a better understanding of the radiation levels [10]. But what if they could see the rays in 3D in the operating room? What if these radiation patterns would no longer be invisible? With mixed reality (MR) this becomes possible. The Microsoft HoloLens (2016) is a mixed reality headset, that can project virtual objects (holograms) in the real world. This leads us to the following research question:

*How can mixed reality be used to simulate a radiation model that provides interventional cardiologists, radiologists and technologists with a better understanding of invisible three-dimensional radiation patterns?*

We answer this question by developing an application for the HoloLens that visualizes the dose rate of three-dimensional X-rays inside an operating room. Using a computer simulation of X-radiation, we calculate and visualize the rays inside an operating room

using the HoloLens. Users can interact with virtual objects in the application and immediately see the changes in the visualization. Our objective is to use holograms so interventional cardiologists, radiologists, and technologists get a better understanding of the radiation patterns in the operating room and become better at identifying positions with high radiation levels. Additionally, we want to explore the possibilities of mixed reality headsets for visualizing complex simulations.

## 1.1 List of research questions

When we define the research further, we formulate the following sub-questions that will be answered in each chapter:

- Q1: Which visualization technique is preferred by specialists and technologists for visualizing radiation dose rates?
- Q2: To what extent can an accurate radiation model be simulated using a mixed reality device?
- Q3: To what extent does the visualization lead to specialists and technologists having a better understanding of radiation patterns during a fluoroscopy?
- Q4: To what extent are the specialists and technologists better at identifying positions with high radiation doses inside the operating room during a fluoroscopy?

## 1.2 Hypothesis

In order to test our research questions we formulated hypotheses for each sub-question. For Q1, we believe a three-dimensional point cloud would be the best way to visualize X-rays in a three-dimensional space. A point cloud provides clear data visualizations, without completely obscuring the environment. In physics, X-ray photons are described as having "particle" characteristics [11]. They are often depicted as spheres or circles in literature. We believe this would relate to the mental image users have of X-radiation.

To test Q2, we use the Microsoft HoloLens as a mixed reality device for simulating the radiation model. Based on the specifications provided by Microsoft [12] we believe that the HoloLens has sufficient processing power to simulate an accurate radiation model that can be compared to real-life measurements. However, concessions must be made in accuracy to be able to achieve a sufficient frame rate. Also multiple visualization techniques should be tested to explore the limits of the graphic processing unit (HPU).

Finally, we believe that the application could increase the understanding of radiation patterns of specialists and technologists. They no longer require a mental image to translate two-dimensional images to three-dimensions. They can see in real-time the dangerous zones inside the operating room, which we believe enhances their understanding during real operations. We base this on previous studies that show that a better mental image can increase the level of success for understanding three-dimensional patterns (see section 2.4). If the X-rays can be visualized they are no longer obscure, so the staff can anticipate and adjust their position accordingly. From this we gather that specialists and technologist will have a better understanding of radiation patterns during a fluoroscopy (Q3)

and become better at identifying positions with high radiation doses inside the operating room (Q4). To sum up, we formulate the following hypotheses:

- H1: A three-dimensional point cloud is the most effective visualization technique for specialists and technologists for visualizing radiation doses.
- H2: A mixed reality device is able to simulate an accurate radiation model that can be directly compared to real-life measurements.
- H3: Specialists and technologists have a better understanding of radiation patterns during a fluoroscopy after training with the application.
- H4: Specialists and technologists become better at identifying positions with high radiation doses inside the operating room during a fluoroscopy after training with the application.

## 1.3 Structure

The structure of this thesis is as follows. Chapter 2 provides an overview of relevant literature related to this research and gives a summary of fluoroscopy and radiation exposure. It also discusses the link between mixed reality and spatial ability of humans. The next chapters will answer the sub-questions formulated in section 1.1. In chapter 3 multiple visualization techniques are tested to find the preferred technique for visualizing X-radiation. Chapter 4 explains the details of the application that was used to assess the research question and the design choices that were made. The application is validated in chapter 5 to determine if the developed model provides an accurate radiation simulation. Chapter 6 looks at the target group of the application and tests if the application can provide users with a better understanding of radiation patterns. Finally, the thesis results are summarized and the research question is answered in chapter 7.

# Chapter 2

# Background and related work

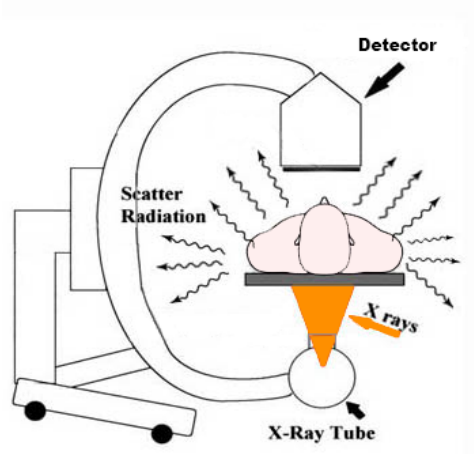
## 2.1 X-radiation and fluoroscopy

Röntgen radiation (also called X-radiation) is electromagnetic radiation that can be used to externally view structures inside the human body. In medical imaging X-radiation is used for projectional radiography, computed tomography, fluoroscopy, and radiotherapy. In this thesis we focus on fluoroscopically guided interventional procedures, because past research determined that interventional cardiologists receive the highest radiation doses of any medical personnel using X-rays [13]–[16]. For a fluoroscopy an X-ray tube is attached to one side of a large C-arm next to the operating table (see figure 2.1). The tube sends X-rays through the patient to the detector which is attached to the other side of the C-arm. Not all X-rays reach the detector, but are scattered from the patient through space. This intensity difference of X-rays that pass through the patient creates the projection images. A fluoroscopy does this in real-time for multiple images, creating a live movie that the specialist can view on a monitor next to the patient.

Fluoroscopy not only exposes the patient to radiation, but also the specialist and the personnel in the room [1]–[5]. The main source of radiation to staff during a fluoroscopy is from scatter radiation reflected from the patient [17]. Radiation exposure to patients and personnel should be limited, because it can result in negative biological effects. They are generally divided into two categories: deterministic and stochastic. Deterministic effects are tissue reactions, such as damage to the eye and skin, that are characterized by a threshold dose [18]–[20]. The amount of damage is directly related to the radiation dose and the severity of the damage increases with the magnitude of the dose [18], [19]. Stochastic effects do not have a minimal threshold dose, but may occur over a longer period of time with the risk of an occurrence increased by higher doses. Possible stochastic effects, such as cancer, increase in probability as a person accumulates radiation dose over time [19]. Therefore, the International Commission on Radiological Protection (ICRP) states that education and training of personnel performing interventional procedures is essential, because good practices will reduce radiation doses to patients and personnel [20].

Radiation exposure of personnel cannot be fully avoided due to the required proximity to the patient, the complexity of the procedure and long exposure times [21], [22]. The amount of radiation that is received depends on the used dose, the exposure time,


**(a)** Fluoroscopy procedure using a C-arm [29].




**(b)** Side view of a C-arm, X-rays and scatter radiation [30].

**Figure 2.1:** Fluoroscopy is an X-ray guided interventional procedure to externally view complex structures inside the human body. An X-ray tube attached to a C-arm sends X-rays through the patient to the detector to create real-time projection images. Not all X-rays reach the detector, but are scattered from the patient through space.

the distance to the radiation source, and the use of shielding by the staff [5], [17], [23]. Previous research reported that shielding and protective clothing are not always effective and that unprotected body parts such as hands, eyes and legs can approach the recommended radiation limits [22]. However, multiple studies evaluated the received dose by personnel during fluoroscopically guided interventional procedures and showed that the dose levels were below the current regulatory occupational dose limits with adequate radiation protection measures [3], [10], [24], [25]. Still, the ALARA principle (As Low As Reasonably Achievable) encourages hospitals to keeping radiation exposure for staff and patients as low as possible [6], [7]. Radiation protection during fluoroscopy can be optimized by increasing the staffs knowledge of radiation dose levels and dose reduction strategies, and include them in their everyday practice as much as possible.[10], [21] One method increasing the staffs knowledge is by providing them with a system that provides real-time information of dose levels [26]–[28].

## 2.2 Previous research

This research follows from previous research done by the Albert Schweitzer hospital. From 2012 to 2013 Slegers et al [10] investigated if real-time radiation dose feedback with coaching can reduce the scatter dose received by pain physicians. They used the Philips DoseAware system [31] to measure and display in real-time the radiation doses to personnel during a procedure. The Philips DoseAware system is a system that measures radiation doses using radiation dose trackers worn on the torso by personnel. Their research consisted of three stages. First, a “blind phase” where only the radiation was measured but not communicated to the staff. Second, the pain physician could see his

received scattering dose on a monitor. Third, the pain physician was trained using dose profiles and supported by a coach during the procedure. The dose profiles were created by the Albert Schweitzer hospital and visualize the average scatter radiation for two C-arm positions at three heights: knee, abdomen and eye level (see figure 2.2). In the third stage, the profiles were used to train the physician between procedures and the coach gave instructions during the procedure to reduce the received dose. The researchers found that the real-time display of the radiation dose by the DoseAware system did not reduce the dose received by the pain physician. However, the third stage with the active coaching reduced the amount of scatter radiation that was received by almost 50%. The authors state that these dose profiles allowed the physicians to plan in advance the optimal location to stand during a procedure. The profiles increased the physicians' awareness for scatter radiation and gave them insight into optimal positioning. Slegers et al concluded that knowledge of and real-time coaching on scatter dose profiles reduced the radiation exposure during interventional pain procedures. In this thesis, we built upon this idea and use three-dimensional mixed reality visualizations to increase the specialists' knowledge of scatter radiation so they become better at identifying positions with high radiation doses.

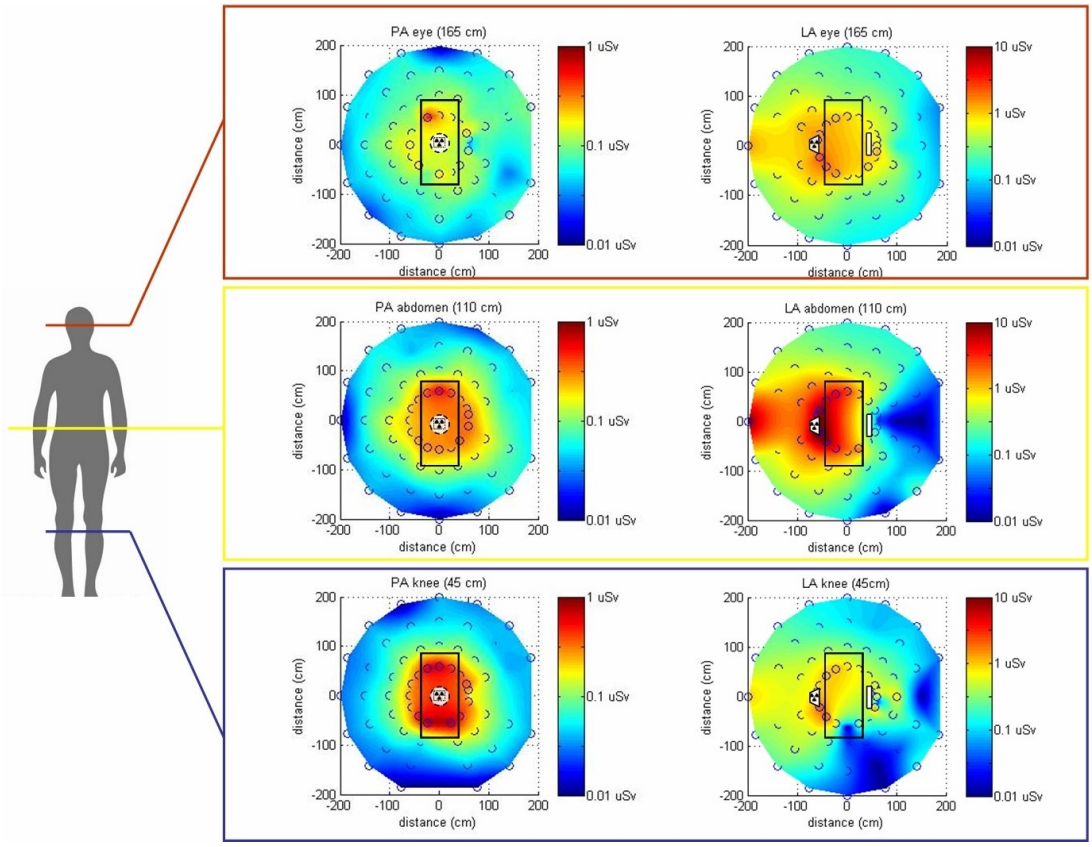



**Figure 2.2:** 2D radiation profiles created by the Albert Schweitzer hospital to visualize radiation doses during a fluoroscopy [10]. The radiation dose has been measured at 190 data points in the operating room at three different heights. Using interpolation these top views are made for two frequently used positions of the C-arm: posteroanterior (PA) and lateral (LA).

## 2.3 Mixed Reality

In this thesis we use mixed reality (MR) to visualize three-dimensional radiation patterns. In this section we discuss the advantages and challenges of a head-mounted MR device.

### 2.3.1 Microsoft HoloLens

The device that will be used for this project is the Microsoft HoloLens [32], which is a mixed reality head mounted device that can display three-dimensional virtual holograms and allows the holograms to interact with objects in the real world (see figure 2.3a). Using head-tracking technology the user's gaze can be followed and used as a virtual pointer. Combined with a "tapping gesture" (see figure 2.3b) the user can click on holograms, which works the same way as clicking on a icon with a mouse on a regular computer. Built-in spatial mapping software provides 3D information of the world, which is used to determine the HoloLens' position and place holograms in the room. Since the HoloLens is wireless, all processing power is inside the headset itself [12]. This includes the CPU, GPU and Microsoft's unique Holographic Processing Unit (HPU). The latter processes all information coming from the on-board sensors, such as the head-tracking cameras and the infrared camera. The HoloLens relies on its internal battery that provides 2-3 hours of active use. It can also be used while charging with the use of a long cable, which limits the space to walk around in. There are other mixed reality devices available, but after comparison the HoloLens was deemed most suitable for this thesis.

**(a)** The Microsoft HoloLens.


**(b)** The HoloLens mainly requires the "tapping gesture" to interact with holograms.

**Figure 2.3:** The Microsoft HoloLens is a mixed reality head mounted device that can display three-dimensional virtual holograms in the real world [32].

### 2.3.2 Advantages

One of the main advantages of mixed reality is the possibility to still be able to see and interact with the real world. In virtual reality the user is completely closed off from reality. Augmented and mixed reality add virtual elements to the world [33], allowing the user to see an enhanced version of the real world. An important advantage of the HoloLens is that it is a head-mounted device. The user has his hands free to interact with the device,

but also to participate in activities in the real world. The second advantage is that the device has two screens right before the user's eyes. These two screens combined allow the user to see three-dimensional holograms. A single-monitor device, such as a tablet or smartphone, can only create the illusion of three-dimensional images by movement. For the visualization of radiation in a three-dimensional space, this feature becomes very important. Another advantage of the HoloLens compared to similar devices, is its independence from other hardware. The HoloLens does not require to be plugged into an external computer. All components are built inside the headset and an OS controls the entire system.

### 2.3.3 Challenges

Mixed and virtual reality devices show three-dimensional objects in the real world that do not physically exist. The technique sometimes causes unwanted side effects such as eyestrain, headaches and nausea. These are mainly caused by vergence-accommodation conflicts [34] and the sensation of movement when there is none. Vergence-accommodation conflicts appear when different depth-cues are sent to the brain (see figure 2.4). In this case the display that shows the virtual elements is very close to the user's eyes, however the image "appears" to be further away. This is conflicting information and may result in eyestrain or a headache. The sensation of motion when there is none presents another challenge. For example the user could be experiencing a virtual roller coaster while sitting in a chair. The brain thinks it is moving, yet the entire body is sitting still in the chair. Every user responds differently to the technology, some experience these side effects very strongly and others might not experience them at all. Nonetheless these side effects are an important aspect of altered realities that developers need to take into account when creating applications for such devices. The HoloLens has a battery life of 2 to 3 hours for active use. All applications have to be optimized and should have minimal power consumption. Even though battery life of the HoloLens is limited, the headset becomes heavy when being worn for a longer period of time. With 0.5 kg weighing down on them, the band around the head and pressure points on the nose can become uncomfortable. Another challenge arises when users who are new to the HoloLens try to interact with it. Although the amount of gestures is fairly limited, it requires some experience to smoothly navigate. It is up to developers to take into account these challenges when creating applications that perform optimally the HoloLens.

## 2.4 Mental representation

We discussed the advantages and limitations of mixed reality, and will now review its possible suitability for visualizing radiation patterns and reducing radiation exposure. Why might a two-dimensional image of radiation patterns, such as figure 2.2, not be enough? This relates to human creation and manipulation of mental images of objects. While a specialist is operating, he or she does not have access to the two-dimensional image and instead has to rely on a mental image representation. The accuracy of this mental image is thus very important.

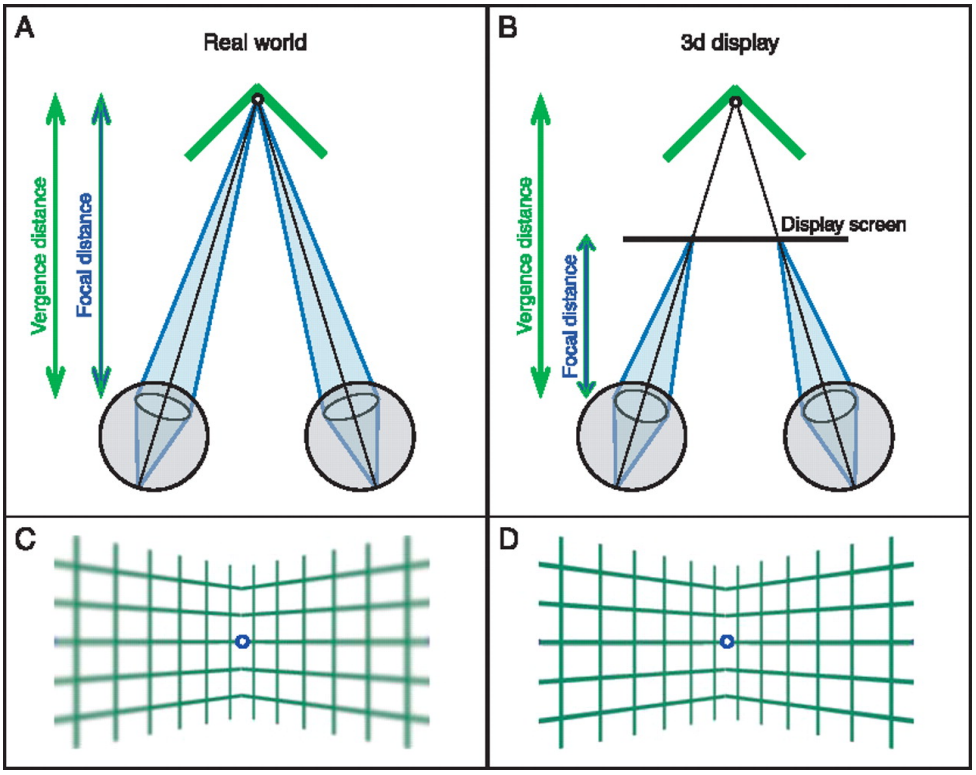
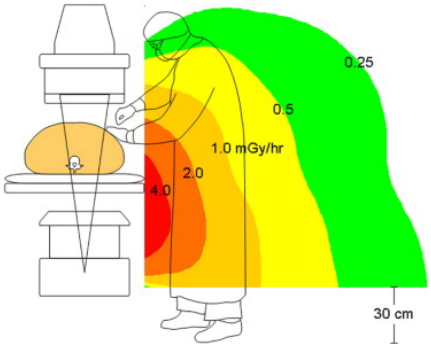


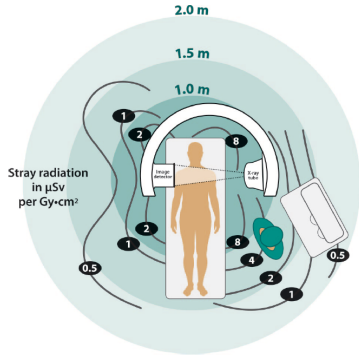

**Figure 2.4:** The vergence-accommodation conflict arises when different depth-cues are sent to the brain. The focal distance (accommodation) to the virtual object differs from the distance it would be if the object was real [35].

### 2.4.1 Cross-sectional images

The original method used by the Albert Schweitzer hospital visualizes radiation doses using two-dimensional images (see figure 2.2). This is currently used by the staff to create a mental representation of the three-dimensional radiation patterns. As can be seen in figure 2.2, multiple slices of the radiation around the operating table are visualized. These slices are also called *cross-sectional images* and are often used in medical imaging [36], for example for computed tomography (CT) or magnetic resonance imaging (MRI) that show anatomical structures as a sequence of two-dimensional images. Other hospitals and researchers also use two-dimensional images to visualize radiation patterns (see figure 2.5). However, to use this information in practice specialists have to mentally translate the two-dimensional images to a three-dimensional model. Research done by the National Research Council has shown that reconstruction of three-dimensional objects from two-dimensional images is difficult [37]. LeClair [38] gives the example of teaching sectional anatomy in medical education. One of the biggest stumbling blocks to mastering anatomy is the students' failure to comprehend the relation between the two-dimensional and three-dimensional representations. Their level of success greatly depends on the "spatial ability" of the individual [39][40]. This shows that two-dimensional cross-sectional images might not be enough for creating accurate cognitive representations.




**(a)** Shueler, 2010 [41].




**(b)** Velentin, 2000 [42]. Reprinted and modified by Anastasian et al, 2011 [18].

**Figure 2.5:** Two-dimensional (or cross-sectional) scatter radiation dose visualizations for fluoroscopically guided interventional procedures.

### 2.4.2 Spatial ability

"Spatial ability is the capacity to understand and remember the spatial relations among objects" [43] or "to understand complex spatial systems and being able to manipulate visual-spatial information" [44]. Spatial ability can be divided into three sub domains: spatial perception, mental rotation, and spatial visualization [45][46]. Spatial perception is defined as the ability to determine spatial relations despite distracting information. Mental rotation allows the quick and accurate rotation of two- or three-dimensional figures in imagination. Spatial visualization includes multi-step tasks that are required to manipulate complex spatial information. It also includes the ability to mentally represent visual images of an object. Spatial ability is important for success in many fields of study [43][46]. Examples are mathematics, natural sciences, engineering and architecture, but also new technologies such as imaging, computer graphics and data visualization require spatial ability to be able to understand the information that is shown. Spatial ability, especially spatial visualization, is relevant to our project. Users have to create a mental image of the radiation patterns and mentally project it in the operating room. Currently the staff of the Albert Schweitzer hospital only has the cross-sectional images (figure 2.2) to assist them. With the 3D visualization, the creation of the mental image should become easier [36].

### 2.4.3 Augmented reality and spatial ability

In 2014 Zhu et al [47] completed an integrative review of more than 2500 papers about augmented reality (AR) in medical education. They found that 96% of the papers claimed that AR is useful for improving health care education. AR improves performance accuracy, shortens learning curves and helps to understand spatial relationships and concepts. So according to their research, AR could be used to improve spatial ability.

Wu et al [36] studied the ability of participants to mentally construct 3D objects from cross-sectional images. A hand-held device was used to reveal hidden objects to the participants using 2D cross-sectional images. They wanted to see if the images should

be presented on a *in situ* display or whether an *ex situ* display would yield the same results. The *in situ* display was an AR device that showed the cross-section at the original location and was movable in space. The *ex situ* display showed the image on a remote CRT monitor and had no spatial movement capabilities. The final results showed that the *in situ* AR version with spatial information was superior to the *ex situ* version. This supports our idea for creating an AR 3D visualization of radiation and showing it in the original location, the operating room, with spatial movement.

## 2.5 Related work

To our knowledge, few researchers have explored the possibilities of augmented - or mixed reality for visualizing radiation patterns inside the operating room. In 2014, Rodas and Padoy developed an augmented reality application that visualizes X-rays from guided minimally invasive procedures [48]. In the following years they further improved and developed their application [16], [49]. Their research contains similarities to our project, mainly using augmented reality to visualize radiation patterns inside the operating room. They used a hand-held screen to display information related to radiation safety in a mobile augmented reality (AR) manner (see figure 2.6). Using ceiling-mounted cameras and sensors they tracked the observer's viewpoint. Their system allows users to see the three-dimensional radiation and provides an overlay of the radiation on the surface of the patient and operating table. They state that such an AR application can greatly improve clinicians' awareness of radiation exposure and reduce overexposure risks.

Our research takes this concept one step further and presents a fully stand-alone radiation simulation on a head-mounted mixed reality device. Our system does not rely on externally placed cameras in the operating room or pre-calculated radiation models. The application runs by itself and nothing besides the HoloLens is needed. Additionally, our application can be used to view radiation patterns in actual 3D, as each eye has a separate screen (as described in section 2.3.2) opposed to the two-dimensional hand-held screen used by Rodas et al. [16].

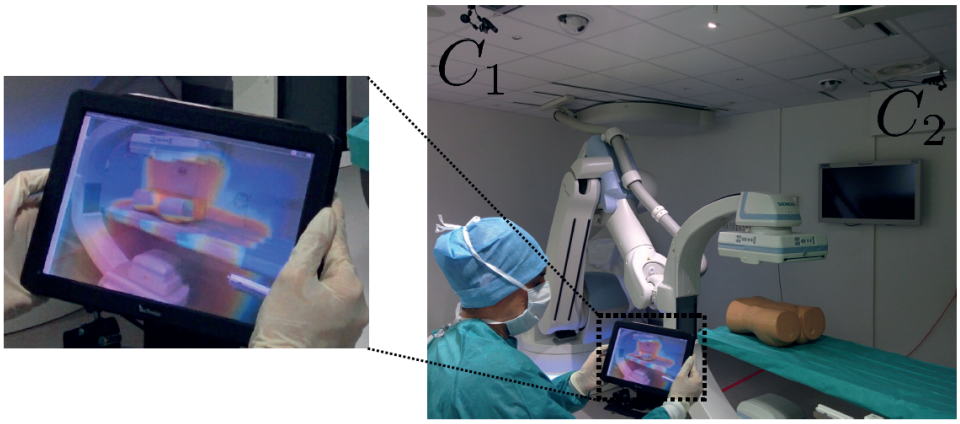



**Figure 2.6:** Mobile AR system for radiation awareness composed of two RGB-D cameras fixed to the ceiling of the OR and a third one attached to a hand-held screen. Reprinted from Rodas et al, 2017 [16].

# Chapter 3

# X-radiation visualization

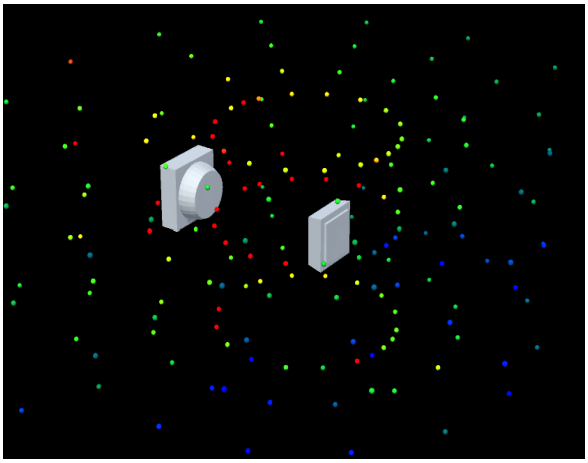
The first part of our research was aimed at determining a method to visualize X-radiation, since X-rays are invisible to the human eye. How would we visualize X-rays in three-dimensions using the HoloLens? In this chapter we answer sub-question:

- Q1: Which visualization technique is preferred by specialists and technologists for visualizing radiation dose rates?

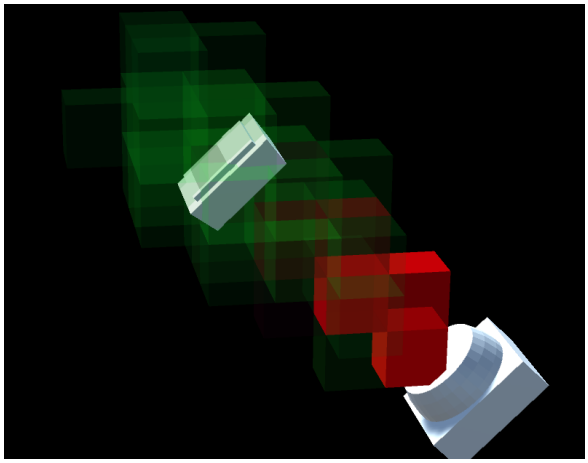
We developed multiple visualization techniques and conducted user tests to find the most effective technique. The developed techniques were solely visual and did not have an underlying physics model. The chosen technique is further developed and used in the final application.

## 3.1 Visualization techniques

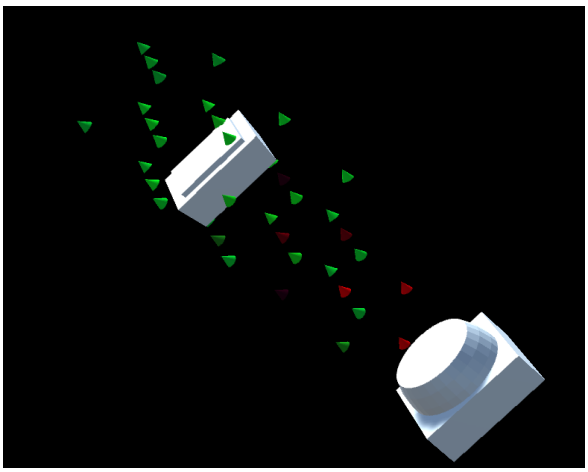
We developed four different visualization techniques: static spheres, voxels, vector field, and moving particles (see figure 3.1). These visualization techniques were created in consultation with the Albert Schweitzer hospital. One of the methods used by the Albert Schweitzer hospital to visualize radiation doses is a heat map (see figure 2.2). Using color they show the dangerous and safer positions in the operating room. We translated this idea from 2D to 3D: three-dimensional objects visualizing the radiation intensity at specific points. We tested three different object shapes: spheres, cubes, and cones. The spheres (figure 3.1a) are "static" objects and use color, size, and transparency to visualize the radiation intensity. Static means the object remains in the same position regardless of radiation patterns or movement from the user. The cubes (also called voxels), are static volumes closely packed together that look similar to a cloud (figure 3.1b). Transparency allows the user to see multiple voxels behind each other. The third technique (figure 3.1c) is similar to the spheres, but adds the feature of pointing in the direction of the X-ray. The cones create a vector field that show the user where the X-rays are coming from. Each individual cone remains in the same position and rotates towards the correct direction.



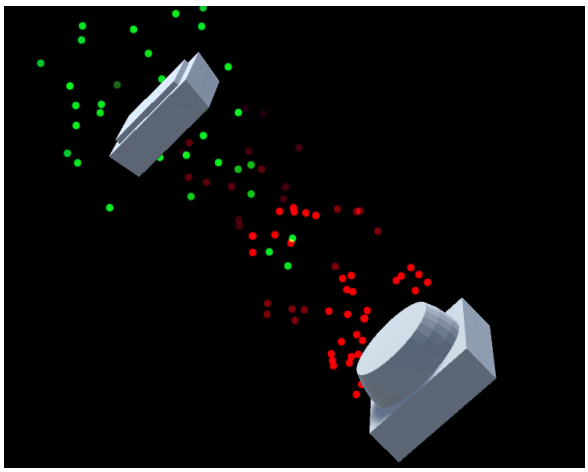
**(a)** Spheres: static spheres in space that use size, color, and transparency to show the radiation intensity.



**(b)** Voxels: static cubes in space that use color and transparency to show the radiation intensity.



**(c)** Vector field: static cones that point in the average direction of the X-radiation. It uses color and transparency to show the radiation intensity.



**(d)** Moving particles: circular shapes that move in the average direction of the X-radiation. It uses color and particle density to show the radiation intensity.

**Figure 3.1:** The different visualization techniques that were developed for visualizing X-radiation. The moving particles implementation (d) was preferred by the participants of the user test.

Unlike the other techniques, the fourth technique is not static and uses moving particles (see figure 3.1d). In physics, X-ray photons are described as having "wave" and "particle" characteristics [11]. When visualizing their behaviour in literature, photons are often depicted as spheres or circles. We used this to create small circles that move in the direction of the X-rays. This creates the effect that the user is able to see the "photons" moving through space. Color and particle density show the radiation intensity. The particles move at a fixed speed that is comfortable to the eyes and performs well at lower frame rates.

## 3.2 Method

The goal of this user test was to find the most effective visualization technique. A questionnaire on paper was used to evaluate each technique (see appendix A.1). A five-point Likert scale was used to rate four statements about each visualization technique:

1. The visualization provides a clear image of radiation.
2. The visualization confirms my mental image of radiation.
3. I trust the visualization provides a reliable image.
4. The visualization could be used for training purposes.

They were rated from: 1 (strongly disagree) to 5 (strongly agree). Additionally, each participant was asked to order the techniques from most to least favorite. The questionnaire was also used to learn more about the fluoroscopy procedure and the personnel involved. How much time and attention do the participants spend on radiation exposure? Where do they stand during a procedure? And how would they imagine X-radiation to be visualized in 3D? Seven participants tested the visualization techniques on the HoloLens. None of the participants was color blind. They were employees of the radiology, cardiology, and medical physics department of the Albert Schweitzer hospital:

- 3 medical physicists (of which one student)
- 2 cardiac catheterization nurses
- 1 radiologist
- 1 medical nuclear worker

The participants filled in the first part of the questionnaire about their own experience with fluoroscopy procedures and how they would visualize X-radiation. Then they used the application on the HoloLens for ten minutes. Each participant was closely observed while interacting with the application. An additional set of questions regarding the visualization techniques was asked during their time wearing the HoloLens (see appendix A.2). After the HoloLens application, the participants filled in the second part of the questionnaire asking about each visualization technique. A laptop captured the sessions on video for later review.

## 3.3 Results and discussion

The results of the visualization technique ratings can be seen in figure 3.2. In the figure we see that the moving particles had the highest mean rating on all statements. One of the main reasons was the "clarity" of the visualization technique (mean: 4.8). Participants stated that the direction and movement of the particles were very intuitive and that they immediately got a sense of safe and dangerous positions. The moving particles also confirmed their mental image of photons and radiation (mean: 4.5). The reliability of all the techniques was relatively low compared to the other statements. This was the result of a low rating of one participant. The medical physicist stated that none of the visualizations could be physically correct, so as a medical physicist he could not agree. He did agree that the moving particles technique would be adequate for training purposes and the best technique for visualizing X-radiation. This was also the result when participants

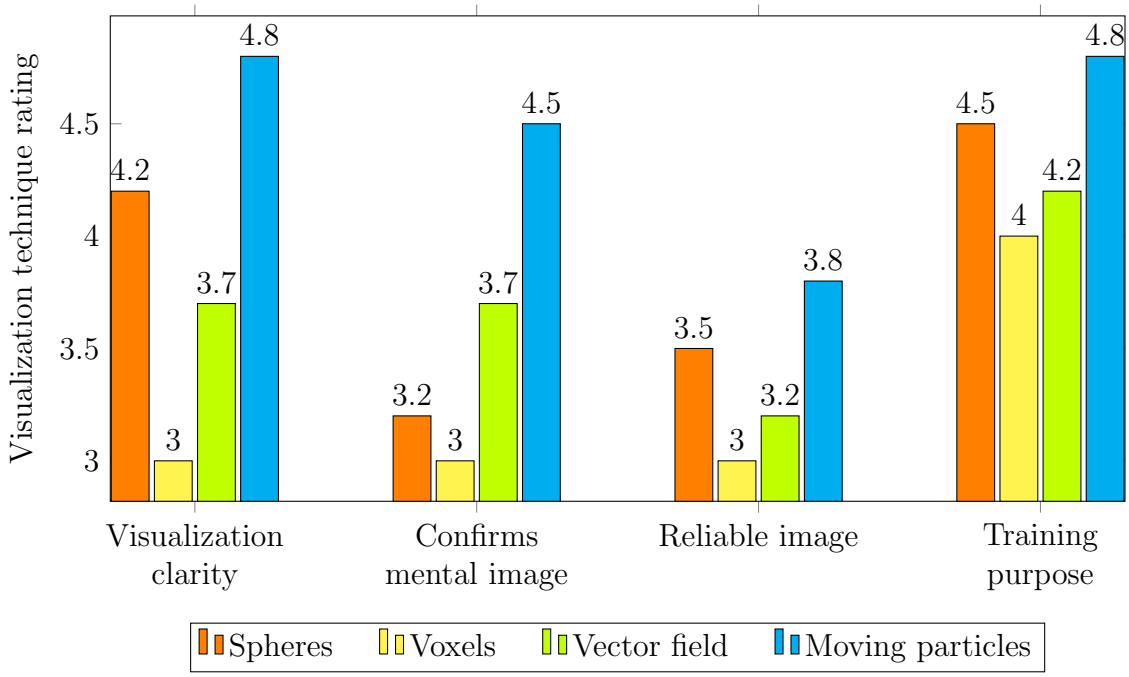



**Figure 3.2:** The questionnaire results mean rating of the visualization techniques. A five-point Likert scale was used to rate four statements about each technique (higher is better).

were asked to order the visualizations from most to least favorite. Only the medical nuclear worker preferred the voxels, however on the questionnaire he gave a higher rating to the moving particles. Finally, the participants responded positively to the HoloLens and all believed this application could be useful for training purposes. Some statements included:

- "The visualization provides a lot of insight into where radiation comes from."
- "The 3D visualization is much more realistic than static 2D images."
- "The visualization allows the user to literally see where it is safer to stand."
- "If the possibility exists to visualize it with the HoloLens, it should be used."

## 3.4 Chapter conclusion

In this chapter we developed and tested four different visualization techniques: static spheres, voxels, vector field, and moving particles. Seven employees of the Albert Schweitzer hospital tested and evaluated the techniques on the HoloLens. The moving particles technique was preferred by the participants and is used in the final application to visualize X-radiation. Additionally, the participants responded positively to the application and the HoloLens, and stated that the application would be useful for training purposes.

# Chapter 4

# Implementation

To answer the main research question we developed an application for the Microsoft HoloLens that visualizes X-radiation patterns. In this chapter we explain the details of the application and the design choices that were made. We provide an overview of the application in section 4.1. In section 4.2, we describe the particle system that was used to visualize X-radiation and its underlying physics model.

## 4.1 The application

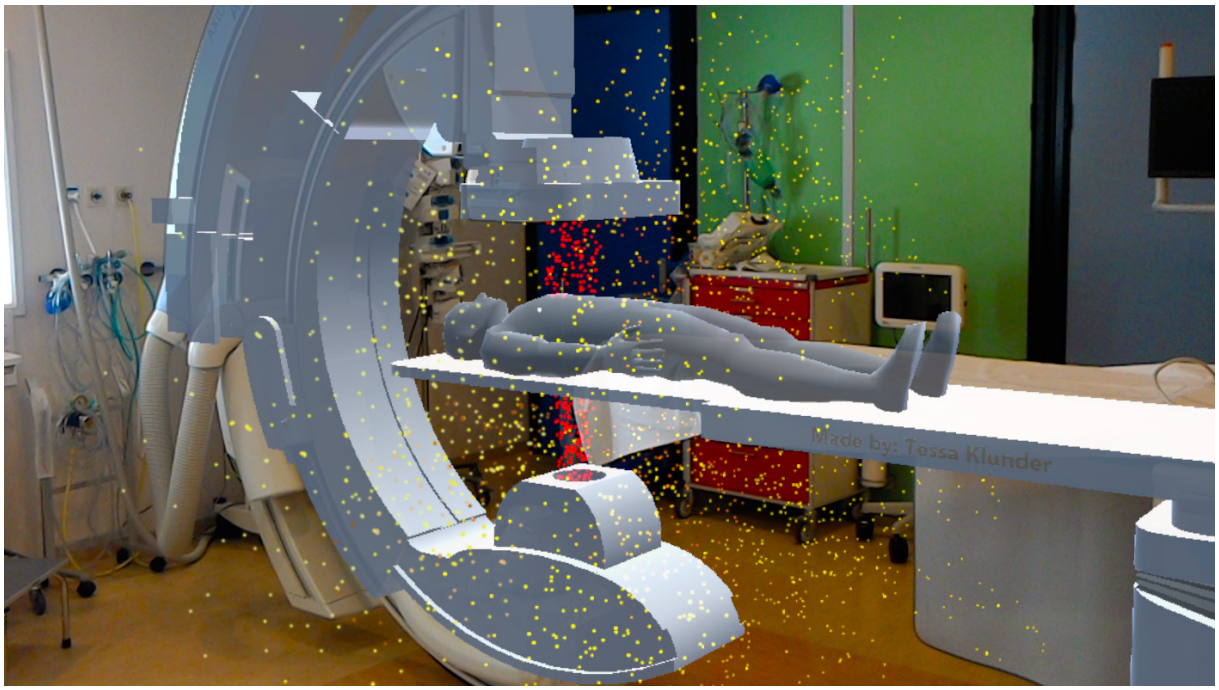



**Figure 4.1:** HoloLens screen capture of the augmented reality application that visualizes X-radiation inside an operating room. The "moving particles" technique was used to visualize X-radiation as described in chapter 3.

### 4.1.1 Functionality

The application was developed in Unity3D together with Visual Studio 2015. It runs on the Microsoft HoloLens Enterprise edition using Universal Windows Platform (UWP). The application simulates and visualizes scatter radiation originating from the patient during a fluoroscopy (see figure 4.1). The application calculates in real-time the radiation intensity at each position in the operating room and uses ray tracing to simulate photons cast from the radiation tube. We will further discuss the underlying physics model in section 4.2. Multiple settings can be adjusted inside the application (see figure 4.2). The effects of these changes are immediately visible in the simulation. A user interface (UI) allows the user to select buttons using the HoloLens Air tap gesture [50], a hand gesture that is recognized by the cameras of the HoloLens.

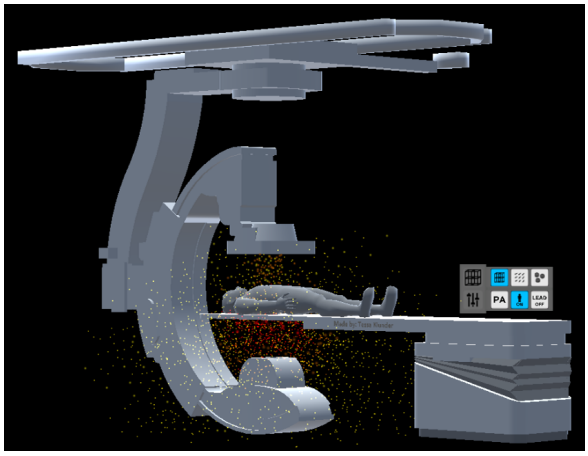
The first option in the UI changes the position of the C-arm from posteroanterior (PA) to lateral (LA), and vice versa. PA is a vertical position were the radiation tube is below the patient and the detector above (see figure 4.2a). LA is a horizontal position were the tube and the detector are at each side of the patient (see figure 4.2b). These two positions were chosen in consultation with the Albert Schweitzer hospital, mainly because they were also used in their previous research and current radiation briefings, and because they are extremes. Additionally, their previous research measured radiation doses for these positions which allows the comparison of radiation patterns. PA is also often used in fluoroscopy procedures.

The second option places lead protective shields in the scene (see figure 4.2c). Lead shields protect personnel from radiation and reduce the effective dose. The shields simulate lead acrylic with a lead equivalent of 0.50 mm. They are placed at a fixed position where the specialist generally stands. It informs the user about the importance of correct shield placement.

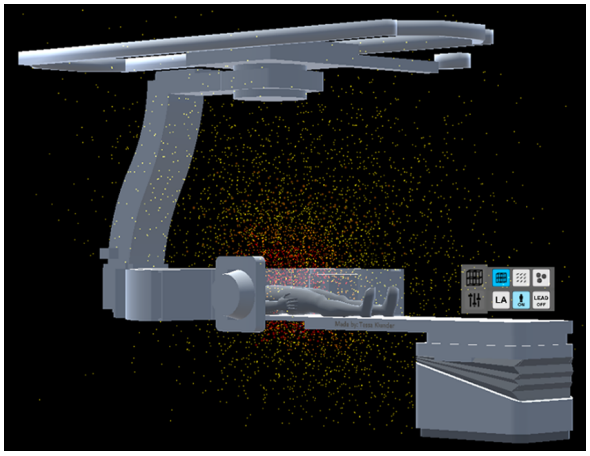
The final option lets the user remove the patient (or manikin) from the operating table. This emphasizes the main cause of scatter radiation; the patient. If the tube is turned on without a patient, the radiation hits the detector without (much) scatter radiation. Interaction with matter such as tissue and bone causes photons to scatter in a different direction. This scatter radiation is what finally hits personnel.

### 4.1.2 Sound

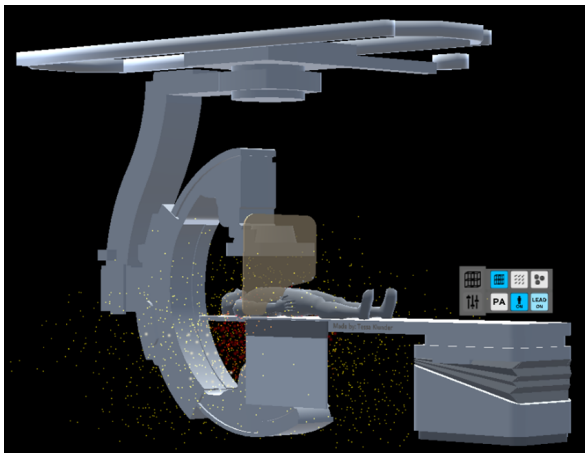
To provide the user with another cue for the amount of radiation they receive, the sound of a Geiger counter is played. When a user walks around with the HoloLens, its position is tracked by the application. Using this position, the amount of radiation is calculated for the voxels that the user is standing in. A vertical line is traced downwards from the HoloLens position to accumulate all the radiation from the voxels below. Based on this value the Geiger counter frequency is adjusted in real-time.



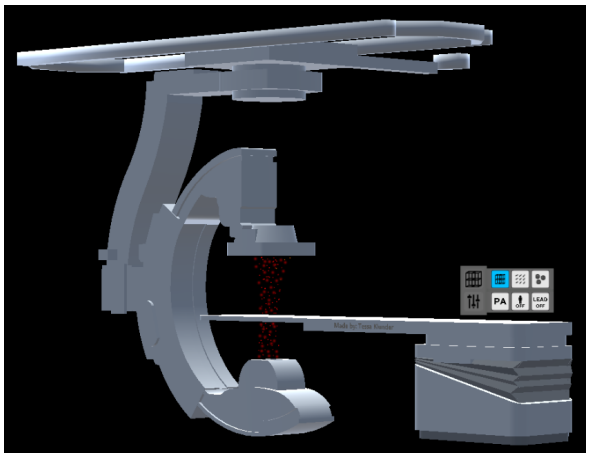

**(a)** The C-arm position can be changed to posteroanterior (PA).




**(b)** The C-arm position can be changed to lateral (LA).




**(c)** Lead protective shields can be turned on to see the reduction in radiation intensity behind the shields.




**(d)** The user can remove the manikin from the table to see the effect of scatter radiation from the patient.

**Figure 4.2:** The application in Unity3D. The user can change settings in the application using the user interface. The effects of these changes are immediately visible in the simulation.

### 4.1.3 Tutorial

A tutorial was added to help the user to interact with the application. At the start of the application the user is informed about the HoloLens' hand gestures and head movements. The HoloLens provides the user with a cursor at the center of the screen. This cursor can be moved by the users head movement. Hand gestures are used for interacting with the UI and for the placement of the operating table. The application requires the user to place the virtual table on the floor before starting the simulation. The user can rotate and drag the table to the desired position. This allows the application to be used outside of the operating room by simulating a virtual operating table. Once the table is placed, the simulation is constructed around the table position.

## 4.2 Radiation simulation

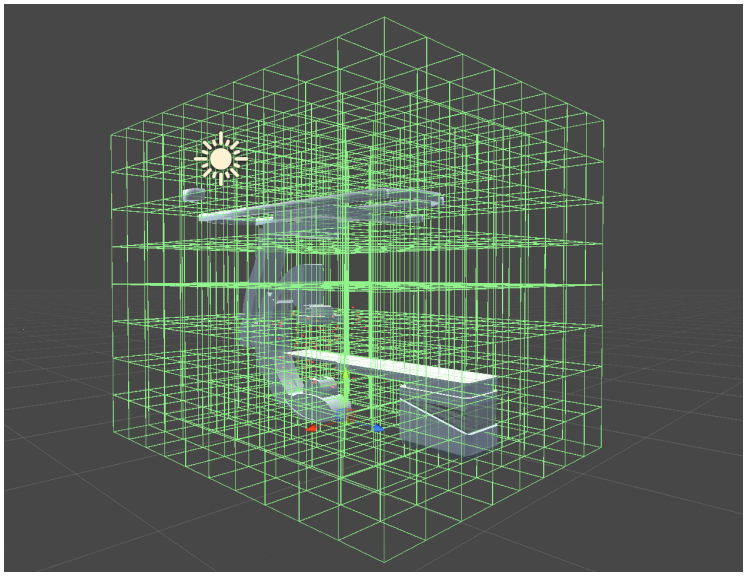
In chapter 3 we tested multiple visualization techniques for visualizing X-radiation. The "moving particles" visualization was preferred by the participants of the user test (see figure 4.1). In this section we describe the implementation of the visualization method using invisible voxels, particle systems, and the underlying physics model of photon interactions.

### 4.2.1 Voxel system and moving particles

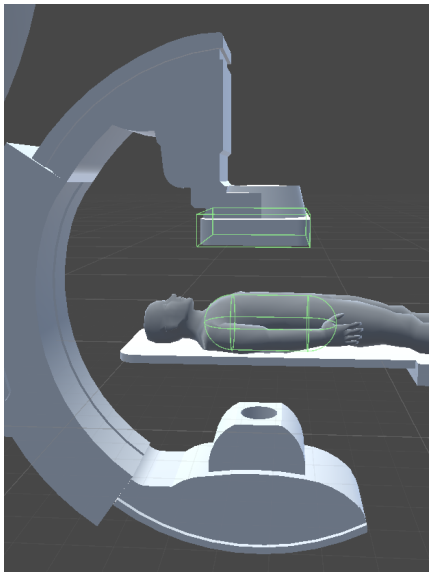
To visualize the moving particles, the standard particle system from Unity3D is used. In games and simulations, particle systems are used for dynamic effects like moving liquids, smoke, clouds, and flames [51]. Many parameters can be changed in a particle system, such as the number of particles, speed, direction, and appearance. These parameters affect an entire particle system. In our simulation the amount of radiation varies for each position in space, so a single particle system would not suffice. As a solution, we segment the three-dimensional space around the operating table in voxels (see figure 4.3a). A voxel is a cube that defines a point in three-dimensional space. We can use each voxel to visualize the radiation in that point. The size of the voxels can be manually adjusted, but we found 15 centimeters to be the optimal voxel size for balancing performance and accuracy. The total space covered by the voxels is 3m x 2.4m x 3m (w x h x d), this results in a total of 6400 voxels.

Each voxel contains its own particle system for visualizing radiation. It creates the illusion that a single particle can be followed through space, when instead it stays within the boundaries of the voxel. To get the correct parameters for the particle system, each voxel stores the average radiation intensity and direction at that point. These values are obtained by the underlying physics model which will be discussed in subsections 4.2.2 and 4.2.3. The voxel values are used by the particle system to show the amount of radiation. The average intensity is visualized using particle density and color. The average direction controls the movement of the particles. A fixed speed for the particles was chosen, which is comfortable to the eyes and also prevents color separation [52]. Color separation on the HoloLens occurs due to its color sequential display: it flashes the color channels of red-green-blue-green sequentially at 60Hz. If a hologram moves too fast, the colors separate and create a rainbow-effect.

There are also some limitations to this method of individual particle systems. Mainly that it takes up a significant amount of memory space and graphic processing power. After testing multiple configurations, we found that this can be reduced by limiting the number of voxels and removing any unnecessary components. Two-dimensional sprites were used for each particle, which is less demanding on the Holographic Processing Unit than three-dimensional objects. Additionally, voxels that do not receive any significant radiation are temporarily "turned off" until they do.



**(a)** The underlying voxel system for calculating radiation intensity. The voxel size was increased from 15cm to 50cm for illustration purpose.



**(b)** Collision boxes have been placed inside the detector and manikin to interact with rays.

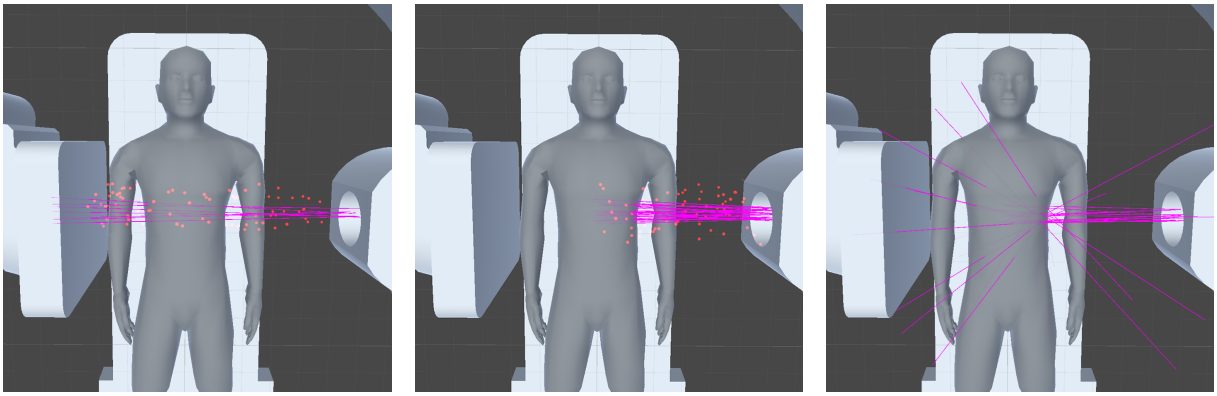
**Figure 4.3:** Screen captures of the application in Unity3D showing the underlying voxels and collision boxes used for collision detection with the photon rays. These boxes are not visible to the user on the HoloLens.

### 4.2.2 Ray tracing

With the three-dimensional space divided into voxels, we can simulate X-rays. We achieve this by implementing a ray tracing system. Ray tracing is used in computer graphics to create images of three-dimensional scenes. It calculates the color of an image pixel by casting a ray through the pixel into the scene. Depending on the object it hits, the ray will continue to any relevant light sources to calculate the correct illumination. We use this approach to trace photon "rays" that are sent from the tube.

We achieve this with Unity3D's built-in ray casting system. It provides the possibility to shoot rays in a given direction with a fixed length. 10000 rays are shot from the radiation tube in a square cone as if they passed through a diaphragm. These rays are shot randomly within the space of the diaphragm. Since the simulation has to be able to adjust to changes, the rays are reset and recalculated after each pass. To improve performance, the simulation is updated after $n$ frames. This limits the number of rays that have to be calculated each frame, while still using all 10000 rays in one update. Since the rays have a random direction each update, it resembles a Monte Carlo simulation. However the values are not kept the entire simulation, because of possible changes in C-arm position or lead shields.

The rays can hit objects in the scene, such as the patient and the detector. They are divided in three collision layers: tissue, lead, and air. The patient is tissue, the detector and lead shields are lead, and the invisible voxels are air. An example of collision volumes can be seen in figure 4.3b. When a ray hits tissue or a lead object, it has an interaction



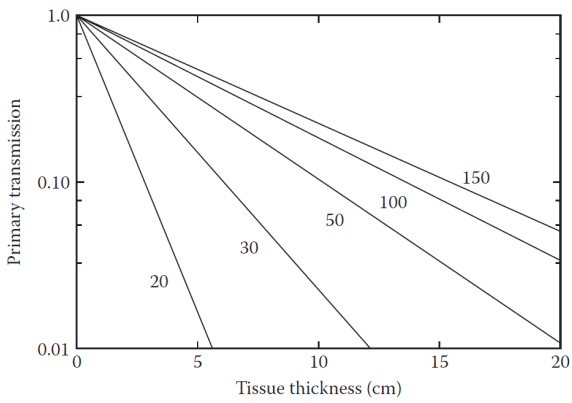
**(a)** Transmission. **(b)** Absorption. **(c)** Scattering.

**Figure 4.4:** Screen captures of the application in Unity3D showing the rays (pink) used for simulating X-ray photon interaction with matter. Three different events are possible: transmission, absorption, and scattering. These rays are not visible to the user on the HoloLens.

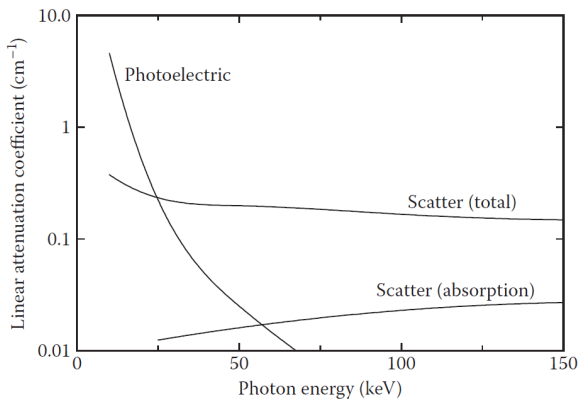
with matter. This can result in multiple events. We will discuss photon interactions with matter in more detail in section 4.2.3. Besides matter, a ray also hits voxels belonging to the air layer. These collisions are used to determine the amount of radiation for each point in space. When a ray hits a voxel it sends its radiation values to the voxel. This contains the ray's intensity and direction. The voxel stores this information from all rays that pass through it. It calculates an average direction and intensity, which are visualized by its particle system. The voxels can only simulate one ray direction per system. We tested how many systems were needed and found that only secondary radiation is relevant. The primary radiation beam is focused on the patient, so it will not hit any bystanders. We visualize this primary beam with a separate particle system. This greatly improves performance, because it means less particle systems to display and store in memory. Tertiary radiation is not simulated either, because there is a limited number of objects to scatter against. Since each scatter interaction also reduces the photon energy, it becomes less significant to the radiation patterns. This way we can improve application performance and memory use without loosing too much accuracy.

### 4.2.3 X-ray interactions with matter

X-ray projection images are created by X-rays that pass through the body and reach the detector. Not all X-rays arrive at the detector due to interactions along the way. There are four basic X-ray interactions: photoelectric absorption, Rayleigh scattering, Compton scattering, and pair production [11]. The HoloLens has limited processing power, which means we cannot implement all X-ray interactions. Our simulation assumes a mono-energetic X-ray tube output with a photon energy of 140 keV, this helps us limit the number of interactions. Photoelectric absorption happens at lower photon energies in soft tissue (see figure 4.5b), so we implemented absorption caused by scattering. Similarly, pair production solely occurs when the photon has a greater energy than 1.02 MeV, which is not the case in our simulation. According to Seibert and Boone [11], Rayleigh scattering only happens in 5% of all scattering events. Due to this relatively low occurrence, we focused




**(a)** Transmission of mono-energetic photons through soft tissue for various photon energies.




**(b)** Variation of the linear attenuation coefficient with photon energy for soft tissue.

**Figure 4.5:** The transmission of photons and the amount of photons that is absorbed or scattered. Reprinted from *Webb's Physics of Medical Imaging* by Flower [53].

on Compton scattering. In this section we explain our implementation of: transmission, absorption, and (Compton) scattering (see figure 4.4).

### Transmission and absorption

The amount of radiation that passes through a material can be determined with the linear attenuation coefficient. This so called "stopping power" represents the probability of attenuation per centimeter of material. It depends on the X-ray photon energy and the physical density of the material (see figure 4.5a). For $N_0$ photons of a mono-energetic beam that hit a material with thickness $x$ and a linear attenuation coefficient $\mu$, we can describe the number of photons that pass through the material as:

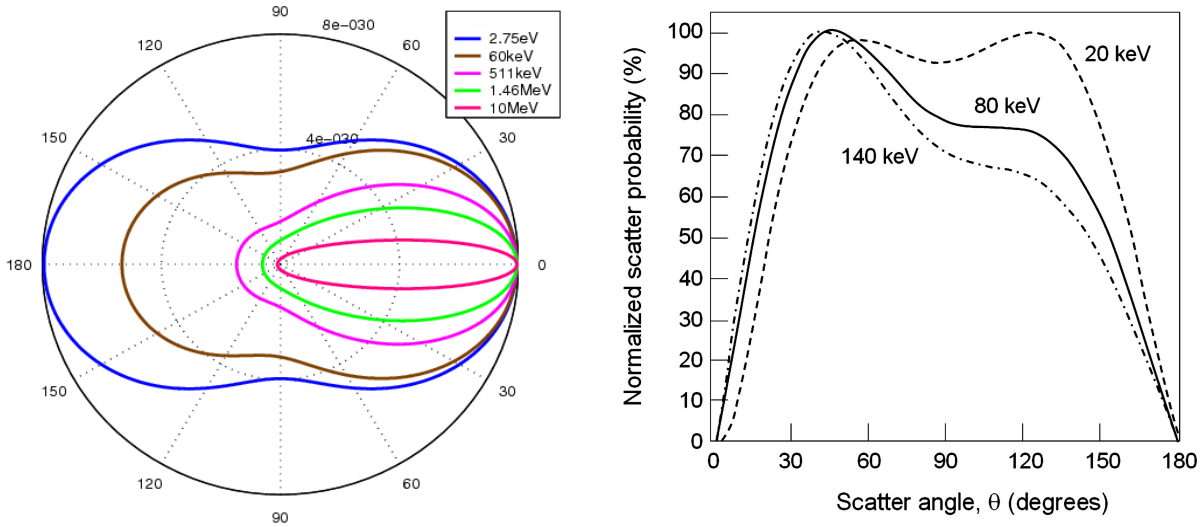
$$N_x = N_0 e^{-\mu x} \tag{4.1}$$

This equation can be further refined by taking into account differences in density for the same material. We apply the mass attenuation coefficient $\mu/\rho$, which normalizes the linear attenuation by the material density. This compensates for the different densities and provides us with a single mass attenuation coefficient per material. From this we get the Lambert-Beers equation:

$$N_x = N_0 e^{-(\mu/\rho)\rho x} \tag{4.2}$$

We use this equation to determine the amount of photons that pass through the patient on the table. We pre-calculated the probabilities and implemented them in the application. In the application we apply this probability by picking a random integer between 0 and 100. If the integer is smaller than $n$, the photon can pass through the tissue without an interaction. If not, this means the photon was either absorbed or scattered.

Absorption occurs when photons lose their energy when travelling through matter. X-ray photons can interact with an electron and transfer all or part of their energy to them.




**(a)** Klein-Nishina distribution of scattering-angle cross sections over a range of commonly encountered photon energies. Reprinted from Wikipedia [54].

**(b)** Plot of scatter distribution probabilities as function of angle relative to incident photon direction. Reprinted from Seibert and Boone [11].

**Figure 4.6:** Photon scatter angles are determined using the Klein-Nishina formula which was translated to probabilities per angle $\theta$ by Seibert and Boone.

This energy can then be sent out by the electron as another photon or be transformed into thermal energy. In figure 4.5b we see that a much larger number of photons is scattered than absorbed. Also the high attenuation coefficient of lead causes the Lambert-Beers equation to approach zero. In the application, we reset the photon ray if it is absorbed and stop any further calculations for this photon. When a ray hits a lead object with sufficient thickness, it will always get absorbed in our simulation.

### Scattering

Absorption is also caused by multiple scatter interactions that continuously reduce the photon's energy and prevent it from exiting the material. We do not simulate all these scatter events to save processing power. Instead we pre-calculated the amount of radiation that is scattered and determine its final scattering angle based on the photon energy and incident angle. The Klein-Nishina formula [55] gives the differential cross section of scattering angles for different photon energies (see figure 4.6a). Seibert and Boone used the formula to plot the scatter distribution probabilities as a function of the scatter angle relative to the incident photon direction (see figure 4.6b).

Using the probabilities from Seibert and Boone, a lookup table (LUT) was created with possible scatter angles for an incoming ray. The size of the table is 100, representing a probability of 100%. For every angle the chance that a photon would scatter in that direction was calculated and added to the LUT depending on its probability. For example, an angle that had a 13% probability was added 13 times to the LUT. A random integer between 0 and 100, would give an angle from the LUT. The LUT contains relative angles

from 0 to 180 degrees, since the distribution is uniform the angle can also "flip" to the other side. For example, a scatter angle of 60 degrees can become 300 degrees.

These angles are two-dimensional. More specifically they represent a rotation around the axis perpendicular to the forward direction. To convert this to three-dimensions, we rotate around the forward direction axis. Again the probabilities are uniform in all directions, so we use a random rotation around the forward axis. This results in a vector in any three-dimensional direction based on the angle probabilities.

## 4.3 Chapter conclusion

The augmented reality application visualizes X-radiation inside an operating room. The user can change multiple settings with the user interface: the C-arm position can be changed to posteroanterior (PA) and lateral (LA), lead protective shields can be turned on to see the reduction in radiation intensity behind the shields, and the user can remove the manikin from the table to see the effect of scatter radiation from the patient. The effects of these changes are immediately visible in the simulation. The sound of a Geiger counter is played, to make the user more aware of the amount of radiation they receive. A tutorial was added to help the user to interact with the application.

The radiation was calculated by segmenting the three-dimensional space around the operating table in voxels. Each voxel stores the amount of radiation it receives and has its own particle system for visualizing the radiation. The radiation values are obtained by the underlying physics model. We implemented a ray tracing system that simulates X-rays. The rays can hit objects in the scene, such as the patient and the detector. This results in three possible X-ray interactions: transmission, absorption, and (Compton) scattering. The amount of radiation that passes through a material can be determined with the linear attenuation coefficient. The Klein-Nishina formula gives the differential cross section of scattering angles for different photon energies. The formula can be used to plot the scatter distribution probabilities as a function of the scatter angle relative to the incident photon direction. With these probabilities a lookup table (LUT) was created to determine the scatter direction for an incoming ray.

# Chapter 5

# Model validation

In the previous chapter we described the application for simulating X-radiation. In this chapter we validate if the developed model provides an accurate radiation simulation. We answer sub-question:

- Q2: To what extent can an accurate radiation model be simulated using a mixed reality device?

This question is answered in two ways. First, we compare real life radiation patterns to the simulated model. Second, medical physicists from a different hospital evaluate the simulation.

## 5.1 Radiation pattern comparison

### 5.1.1 Method

To validate the accuracy of the radiation simulation, real-life measured data was used to compare radiation patterns. This data came from previous research done in the Albert Schweitzer hospital [10]. Scatter radiation was measured using the Philips DoseAware system and its personal dosimeters (PDMs). The radiation was measured at three different heights: 45 cm above the floor for the knees, 110 cm for the abdomen, and 165 cm for eye level. A PMMA block, with size 8 x 30 x 30 cm, was placed on the operating table to simulate the surface of a human body. The measurements were done for two positions of the C-arm: posteroanterior (PA) and lateral (LAT). The scatter radiation was measured at 16 angles from the target at a radius of 60 cm, 100 cm, 150 cm, and 200 cm from the center of the table. This was done for all three heights. In our simulated model we replicate these measurements at the same locations in Unity. We use collision detection to find the corresponding voxel at each position. The radiation value for each voxel is stored and plotted in a graph using MATLAB. The model only simulates Compton scattering and uses a fixed photon energy, so we cannot measure realistic radiation doses and instead use arbitrary units. However, we can visualize the radiation patterns by applying a logarithmic scale to the measured values. We visually compare these patterns to the original ones to see whether the simulation provides a realistic image.

### 5.1.2 Results and discussion

Our validation method used the same C-arm positions and measuring points for the scatter radiation. In figure 5.1 the radiation patterns have been plotted. The simulated results are portrayed next to the real-life measurements of the Albert Schweitzer hospital. The values of the simulated model are not directly comparable to the real-life measurements, because the model does not simulate effective dose in $\mu$Sv, but both have a similar logarithmic scale to visualize the patterns.

When comparing the patterns, we see that the they are very similar for both arm positions. The PA position shows that most of the radiation is scattered back down from the patient. This effect occurs due to the density of the patient. A photon has to travel through the entire body without scattering. However, there is a large chance that it will hit something and scatter back. This results in the higher levels of radiation at knee level. The same effect occurs in the horizontal LA position. In this case radiation is scattered back towards the radiation tube. This effect is clearly visible in the simulation model.

In the LA position (figure 5.1b) we see that more radiation is scattered to eye level than knee level. This depends on the height of the radiation tube compared to the patient and the physical structure of the human body. Also the measurements on the eye level (+45cm) are slightly closer to the radiation tube than on the knee level (-65cm).

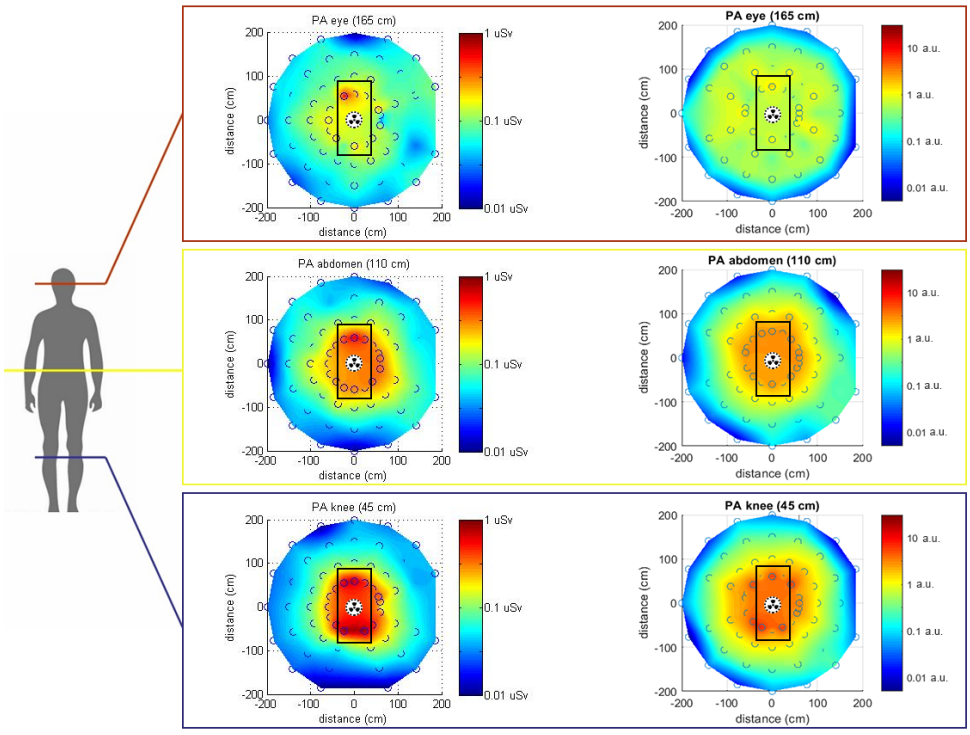
There are also some differences between the two plots. In the PA plot (figure 5.1a) we see that the simulated model has a much wider "cone" of radiation than the real-life measurements. We believe this effect occurs due to the chosen scattering angles. The simulated model uses scattering angles specific to a higher photon energy (140 keV) than the real-life version which has a broad spectrum of energies. When using higher photon energies, there is a higher chance that the photon will scatter in a forward direction (see section 4.2.3). So in the simulated plot we see much more radiation passing through the patient. A second look-up table with different scattering angles for lower photon energies would solve this problem.

Another difference is the size of the "shadow" behind the detector in the LA position (figure 5.1b). This difference is mainly caused by the size of the detector. In the simulation the detector is larger than the real-life version, because a different C-arm model was used. More measurement points fall behind the detector, thus leaving a larger shadow.

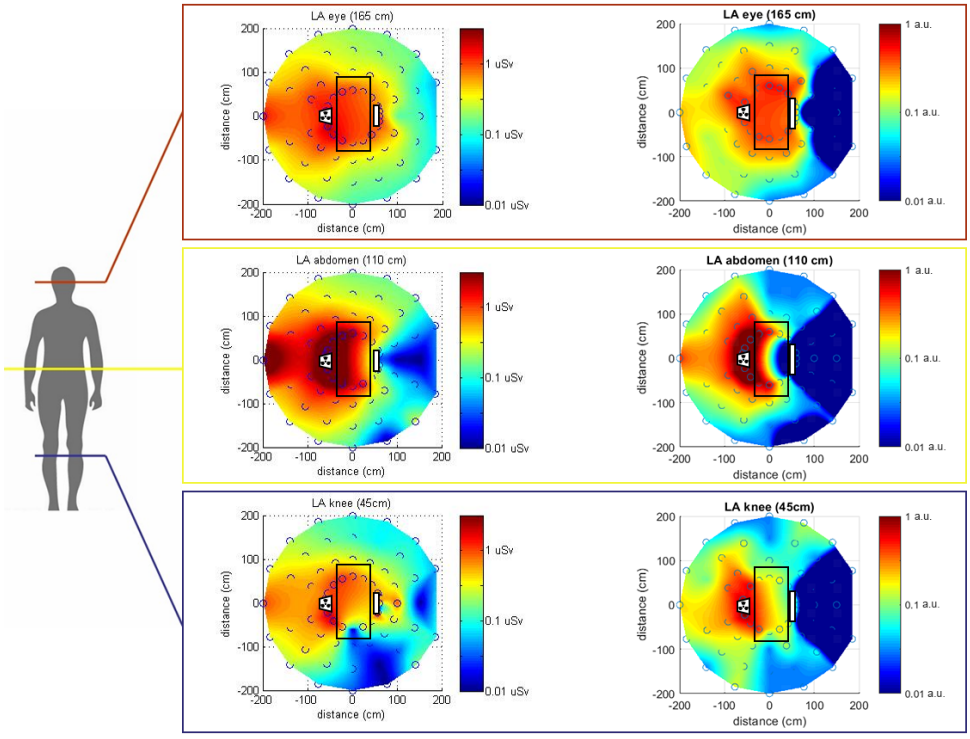
Finally, this model simulates Compton scattering in a simplified form. Other scattering effects such as photoelectric effect and Thomson scattering were not implemented in this version. Additionally, scattering from other objects in the room is not included. We believe these differences might have resulted in the variations between the radiation plots.

## 5.2 Expert opinion

We showed that the simulated model approximates the measured radiation patterns when visually comparing them. Additionally, we wanted an external party to validate the application and its underlying radiation model. Two medical physicists from the radiology department of the University Medical Center Utrecht evaluated the simulation. We asked their opinion about three aspects: the radiation model, the implementation on the HoloLens and possible training purposes of the application in hospitals.




**(a)** Radiation patterns in PA position in real-life (left) and the simulated model (right).




**(b)** Radiation patterns in LA position in real-life (left) and the simulated model (right).

**Figure 5.1:** Plot of radiation patterns of 190 points in real-life [10] and the simulated model. The same positions to measure the amount of radiation were used in real-life and in the simulated model. Radiation doses should not be directly compared, instead this figure focuses on the radiation patterns.

### 5.2.1 Radiation model and technical implementation

The underlying radiation model and its visualization on the HoloLens were approved by the physicists. They considered the interactive ray tracing system to be successful in simulating the effect of photons. Some future improvements would include the addition of multiple photon energies and their different reactions with matter. Also the color and photon density are currently being used to visualize the number of photons. The physicists propose the use of color to visualize photon energies. A user can then see that not all photons have the same energy and thus respond differently to matter. The physicists stated the limited field of view of the HoloLens makes it more difficult to get a complete overview of the simulation. They acknowledge that this is a hardware limitation that could be resolved in the future. The physicists also found the HoloLens' mobility and ease of use strong advantages: "It allows the application to be used anywhere. The option to simulate an operating table allows the simulation to be outside of the operating room. On the other hand the ability to apply it in the operating room is useful as well. The user can immediately see the simulation inside their actual work space and interact with the real world."

### 5.2.2 Usability for training

The University Medical Center Utrecht also uses the Philips DoseAware system to measure and display the received radiation dose to personnel. The medical physicists said: "It is important that personnel are aware of the amount of radiation they receive, that is why we use the Philips DoseAware system. An additional training with the HoloLens to make people more aware of radiation would be valuable." Care must be taken in the way radiation is visualized and presented to the user. If the amount of radiation is exaggerated for visual aesthetic it might shock personnel. According to the physicists the current visualization of radiation is accurate.

### 5.2.3 Future additions

The session with the medical physicists also resulted in some possible future improvements and additions to the simulation:

- Add various photon energies and their different interactions to matter.
- Use color to visualize the different photon energies instead of number of photons.
- Add more intensity levels to the Geiger counter to get a better idea of the amount of radiation the user receives.
- Visualize the amount of radiation as a heatmap on the floor in two dimensions, similar to figure 5.1.

## 5.3 Chapter conclusion

In this chapter we visually compared real radiation patterns with the simulation model. Even though the radiation values could not be directly compared, we can see that the simulated patterns approach reality. Small errors could be solved by implementing more scattering effects and different scattering angles for various photons energies. Adding these features would create a more realistic model, however these subtle changes may not always be visible in 3D. Care must be taken in preventing exaggerated effects. The medical physicists from the University Medical Center Utrecht were impressed by the application and the HoloLens. They deemed the physics model adequate for this application and agreed with the methods that were used. Also the application and the HoloLens can be used anywhere for the training of personnel.

# Chapter 6

# User tests

The final evaluation method tests if the application can provide users with an improved understanding of radiation patterns with the target group. We also assess the participants personal opinion regarding the visualization technique, their perceived learning effect, and the usability of the application. With this research we evaluate the sub-questions:

- Q3: To what extent does the visualization lead to specialists and technologists having a better understanding of radiation patterns during a fluoroscopy?
- Q4: To what extent are the specialists and technologists better at identifying positions with high radiation doses inside the operating room during a fluoroscopy?

User tests were conducted with the application on the HoloLens in the Albert Schweitzer hospital. In this chapter, we explain the method and procedure that were used, and present and discuss the test results.

## 6.1 Method

### 6.1.1 Design

For this research we used an exploratory approach consisting of two parts:

1. Learning effect
2. Assessment of visualization, perceived learning effect and usability

First, we compared the participants' knowledge about radiation patterns and high dose level positions before and after using the application. With this pairwise comparison we determined if their knowledge has improved and if they experienced a learning effect. Second, we evaluated their personal opinion regarding the visualization technique, their perceived learning effect, the usability of the application, and their response to the HoloLens itself. The application and procedure were identical for all participants. The only variable was the difference in location between two sessions due to the limited availability of operating rooms. While participants used the application, their behaviour was observed and their comments were written down.

| Department | **Radiology** | **Cardiac Catheterization** | **Operating Room** |
|---|---|---|---|
| | 2 radiologists<br>4 technologists | 4 cardiologists<br>2 technologists<br>5 nurses | 1 O.R. coordinator<br>1 anaesthetist<br>2 intervention nurses |
| Total | 6 (28.6%) | 11 (52.4%) | 4 (19%) |

**Table 6.1:** Occupation of the participants per department of the Albert Schweitzer hospital.

### 6.1.2 Participants

21 participants took part in the user tests. They were personnel from the Radiology, Cardiac catheterization, and Operating Room departments of the Albert Schweitzer hospital (see table 6.1). Their work experience in the hospital ranged from 6 months to 40 years (mean 12 years). All had experience with fluoroscopy procedures and prior knowledge of Röntgen radiation. The level of knowledge varied depending on their role and department. Their experience with mixed reality or the Microsoft HoloLens was little to none. None of the participants was color blind. Some participants wore glasses which can be worn together with the HoloLens. Two participants had been involved in the earlier test for different visualization techniques (see chapter 3). This did not include the radiation model or anything similar to it, so they were allowed to participate in this user test.

### 6.1.3 Materials

Two Microsoft HoloLens Commercial Suite editions were used for testing. They were provided by the Albert Schweitzer hospital and Capgemini Netherlands. They were identical and used to test two participants simultaneously. Both devices had the same version of the application installed as described in chapter 4.

Information on radiation safety from the Albert Schweitzer hospital was used to create a questionnaire. It consisted of the two parts as described in the design section: learning effect, and assessment of visualization, perceived learning effect and usability. The questionnaire was handed out on paper to the participants (see appendix B.1). The first part of the questionnaire evaluated whether a learning effect was determined. It compared the participants' understanding of radiation patterns before and after using the application. The results are sorted in four categories: answering correct both times, answering correct only the second time, answering wrong both times, and answering wrong or worse the second time. The questions were derived from the current radiation safety briefing of the Albert Schweitzer hospital.

The second part of the questionnaire assessed the personal opinion of the participants regarding the visualization, perceived learning effect and usability of the application. These three categories were evaluated separately. A five-point Likert scale was used to measure how much participants agreed or disagreed with statements about visualization and usability for training. Did the simulation confirm their idea of radiation patterns? Can they envision a better image of radiation patterns? And do they find the HoloLens a suitable medium for visualizing radiation patterns?

**(a)** The first group in the break room of the O.R. department.

**(b)** The second group in the cardiac catheterization operating room.

**Figure 6.1:** The user tests were held at two different locations in the Albert Schweitzer hospital.

### 6.1.4 Procedure

The user tests took place at two different locations in the Albert Schweitzer hospital: the break room of the O.R. department and a cardiac catheterization operating room (see figure 6.1). The break room was chosen because the operating rooms were unavailable at the time. Due to the different test locations and the possible influence the difference might have on the results, we split the participants into two groups. We will refer to them as group one (break room) and two (cardiac catheterization room).

Apart from the different locations, the procedure for all participants was the same. Before they used the application, the participants filled out the first part of the questionnaire. This included a number of general questions and the first half of the knowledge test. While they were doing the test, the experimenter set up the simulation with the HoloLens. The experimenter helped the participants with putting on the HoloLens and verified if they were seeing the correct simulation. Sometimes two participants were tested at the same time with the two HoloLenses. They had their standalone version of the simulation running and could not interact with each others simulation. The experimenter guided each participant through the different steps inside the application:

1. Make the patient visible to start the scatter radiation simulation.
2. Change the position of the C-arm to the lateral position.
3. Walk through the radiation to hear the effect on the Geiger counter.
4. Turn on the lead shielding to see the effect on the scatter radiation.
5. Explore the simulation freely.

The different steps were executed using a user interface (UI) panel inside the application. The subjects could press buttons using the *tap* gesture from the HoloLens. After the simulation they filled out the second half of the test and the rest of the questionnaire. Some participants made comments during or after the simulation which were written down. Most of the personnel was on duty, so they had a limited amount of time (between 10 to 15 minutes). Chocolate cookies were offered to the participants as reimbursement for their time.

## 6.2 Results

### 6.2.1 Part 1: Learning effect

As explained in the previous section, we split the participants into two groups due to the different locations and its possible influence on the test results. In figure 6.2 the answer comparison for all 21 participants is shown (see appendix B.2 for numerical results). In figure 6.3 the separate results of both groups are plotted.

Figure 6.3 shows a difference in test results between the two groups. The second group performed better for questions 3 and 4 compared to the first group. Question 3 is answered correctly by 33.3% of the first group after seeing the visualization, compared to 100% of the second group. The second group improved their answers by 33.3%, whereas the first group worsened by 33.3%. A smaller difference occurred for question 4; 55.5% of the first group and 91.7% of the second group answered correctly the second time. For this question the second group also improved their answers significantly more than the first group. However, the results also show that some participants worsened after using the application. Mainly the first group showed a lower test score: 11.1% (Q2), 33.3% (Q3), and 22,2% (Q4). The second group worsened by 25.0% for question 2 and 8.3% for question 4.

This difference between the groups was smaller for question 2 about the lead shields. Question 2 had almost the same result for both groups; 55.5% of the first group and 58% of the second group was able to answer it correctly after seeing the visualization. Both groups improved slightly, but also had a group that worsened. Finally, question 1 was answered correctly by all participants the first time.

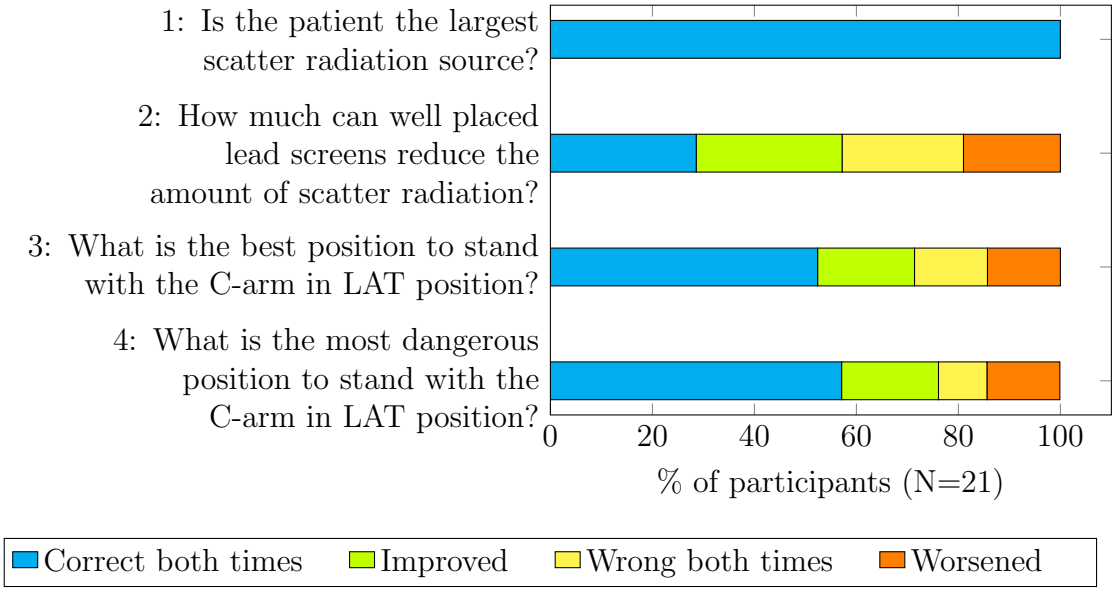
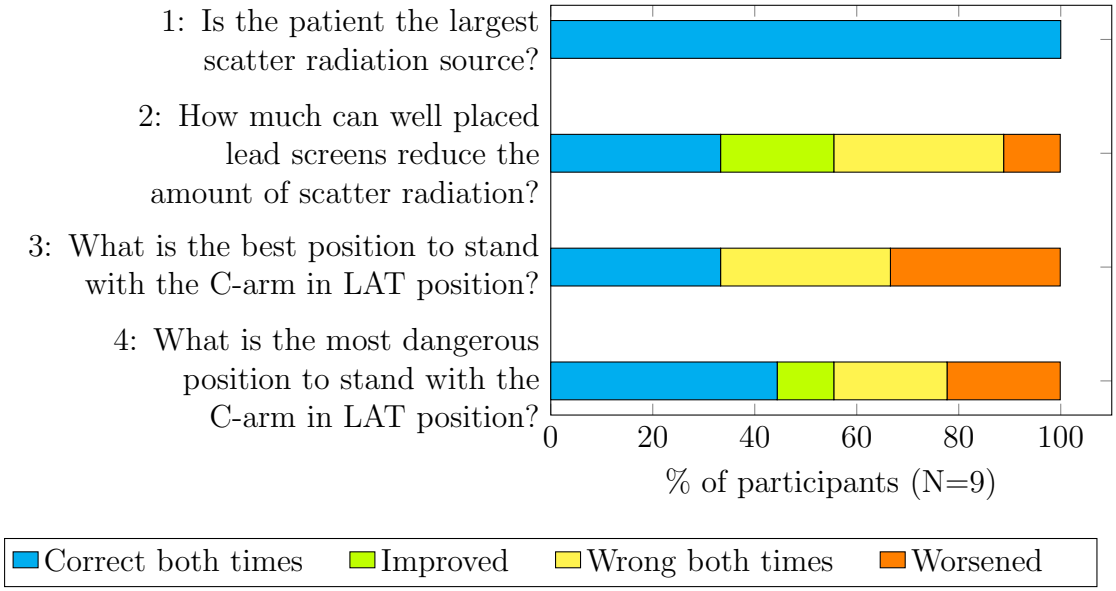
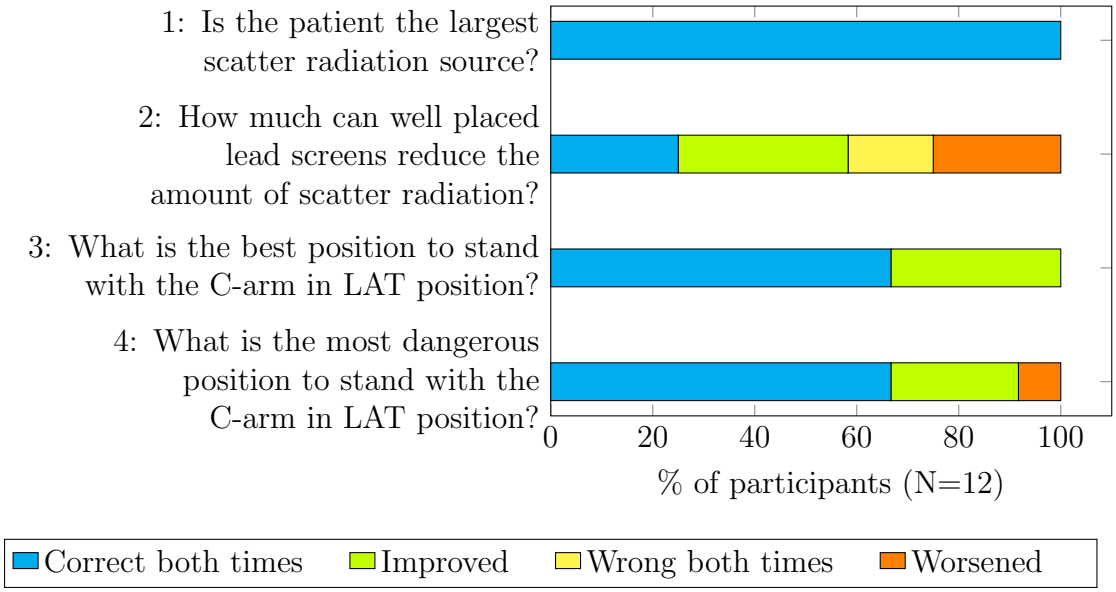



**Figure 6.2:** The comparison of the answers of 21 participants about the learning effect before and after using the application on the HoloLens. There were four possibilities: answering correct both times, answering correct only the second time, answering wrong both times, and answering wrong or worse the second time.




**(a)** Questionnaire results of **the first group**, in the break room.




**(b)** Questionnaire results of **the second group**, in the cardiac catheterization room.

**Figure 6.3:** The comparison of the answers separate for the two groups before and after using the application on the HoloLens about the learning effect. There were four possibilities: answering correct both times, answering correct only the second time, answering wrong both times, and answering wrong or worse the second time.

### 6.2.2 Part 2: Visualization, perceived learning effect and usability

The results of the second part of the questionnaire can be seen in figure 6.4 (see appendix B.2 for numerical results). The stacked bar charts show the distribution of the responses for each statement. The order of the statements has been sorted into the three categories compared to the original questionnaire for better reading. The results of the two groups have been combined in one chart due to the relatively small differences in answers between them.

First, the visualization method was evaluated to see if it confirmed the mental image the participants had of X-radiation. Figure 6.4a shows that for 76% of the participants the model confirmed their image of radiation patterns, 19% remained neutral, and one participant indicated it did not correspond to his/her own image (statement 1). The results of statement 3 shows that 19% of the participants found that the radiation patterns were unclear. The participants were more divided about whether their image of radiation patterns has changed in statement 4. There was a slightly larger group of 43% that said their image has changed. Finally, 81% trusted that the visualized radiation model was reliable.

Besides the measurable learning effect, we also looked at the perceived learning effect experienced by the participants. This was evaluated with statements 6 and 7 (see figure 6.4b). Combining the result from these statements, 67% of the participants declared the visualization has improved their insight and image of radiation patterns.

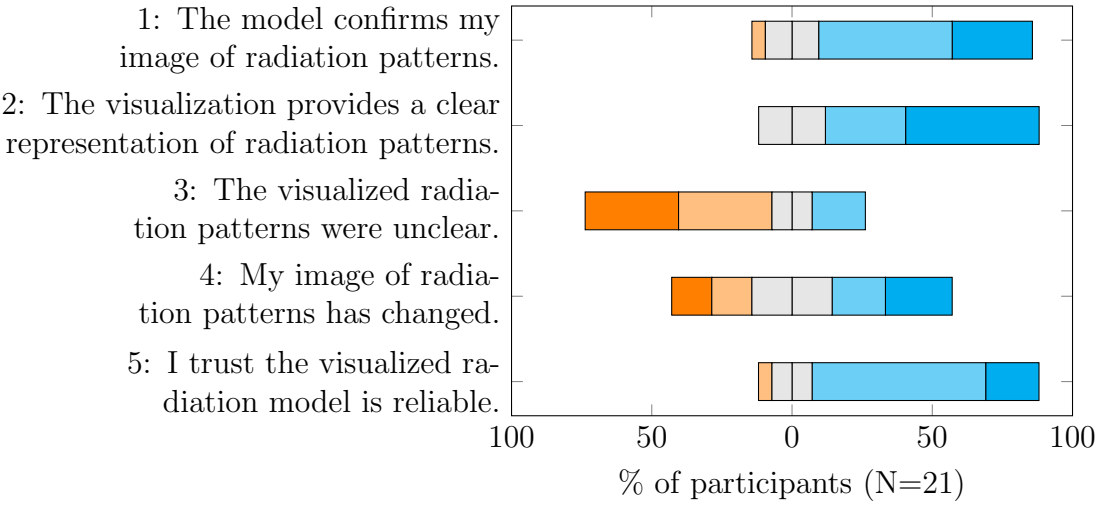
Finally, Figure 6.4c focused on the future possibilities and usability of the application. 57% said they will spend more attention to the amount of radiation they receive during procedures (statement 8). 95% of the participants thinks the visualization could be used for training purposes and 86% would like to use new versions of the application for training. Two participants (9%) found that the current training method in the hospital is better than the visualization (statement 10). Lastly, all participants agreed that the HoloLens is a good method for visualizing radiation patterns (statement 12).

### 6.2.3 Observations and comments

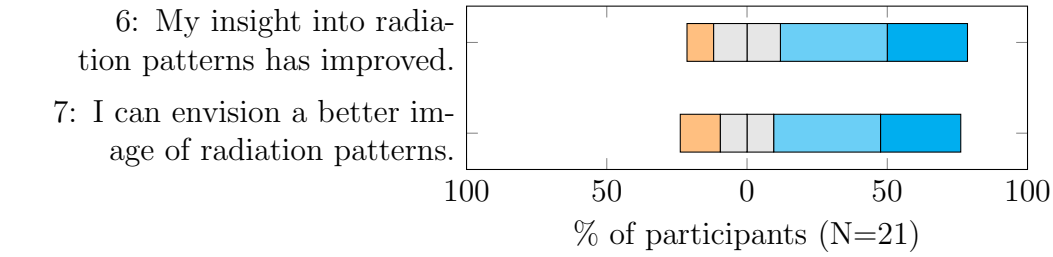
While the participants were using the HoloLens their movements and comments were observed and written down. The most frequent and notable observations are described in this section.

Two participants experienced difficulties when interacting with the HoloLens. To interact with the application and change multiple settings, the participants had to make the *tap* gesture of the HoloLens. This is a built-in hand gesture that can be recognized by the HoloLens' external cameras. It requires practice to learn the gesture so that the HoloLens recognizes it correctly. One participant stated she was "glad to stop the simulation so she no longer had to press any difficult buttons". Other participants experienced no difficulties whatsoever.

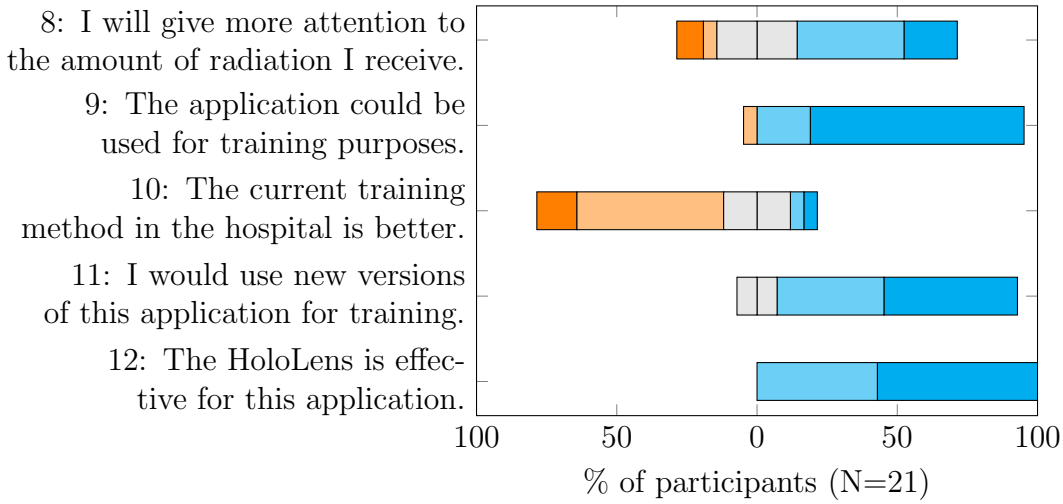
At first participants were hesitant in walking through the simulation. They remained in one position while looking at the application. Once they were advised to move, all participants walked "around" the virtual operating table. They even bumped against




**(a)** Statements about the used visualization and underlying model of the application.




**(b)** Statements about the perceived learning effect of the application.




**(c)** Statements about usability of the application and the HoloLens.


**Figure 6.4:** Questionnaire results of 21 participants after using the application. A five-point Likert scale is used to measure how much they agreed or disagreed with 12 statements. The statements are divided in three categories: visualization, perceived learning effect, and usability.

real objects to avoid moving through any virtual ones. Most of them also commented on this and described it as strange that they automatically did not walk through the simulation even though they knew it was not real.

Lastly, participants could also provide tips and comments about the application.

Mental image:

- *"My image of PA has been confirmed, but LAT was different than I expected. So I will use this knowledge to stand in a different position."*
- *"Do the colors represent the amount of radiation?"*
- *"I thought there would be more particles on the other side of the C-arm."*
- *"I found it difficult to remember the radiation patterns with lead screens and compare it to the scene without. It might be useful to place both scenes next to each other."*

Usability:

- *"The simulation provides a clear and practical image of radiation."*
- *"I would like to use the application live during a procedure."*
- *"I have learned more in five minutes with the HoloLens than during my entire radiation safety training."*

HoloLens:

- *"The HoloLens has a very small field of view."*
- *"The HoloLens is heavy and presses down on my nose."*

## 6.3 Discussion

The aim of the user tests was to evaluate how users experience the application and the possible learning effect it has on them. Since the number of participants is relatively small, we cannot statistically prove the hypotheses. However, the results do provide insight in future possibilities. In this section, we discuss the results and the possible causes.

### 6.3.1 Part 1: Learning effect

Our hypotheses for the sub-questions Q3 and Q4 regarding the learning effect were:

- H3: Specialists and technologists have a better understanding of radiation patterns during a fluoroscopy after training with the application.
- H4: Specialists and technologists become better at identifying positions with high radiation doses inside the operating room during a fluoroscopy after training with the application.

The results from figure 6.3 show that the participants of the second group improved their test results regarding understanding of radiation patterns with 33%. They also became 29% better at identifying positions with high radiation doses in the operating room. However, the first group did not improve their results and an average of 22.2% worsened. Both groups used the same application on the HoloLens and had access to the same information. Yet, the second group had a different result. Before we discuss any factors that contributed to this difference, we must note that the different environments of the user test might have influenced the results. The first group was tested in a break

room in the hospital. The operating rooms were occupied, so this was the only available room large enough for the simulation. During the user tests, other staff members were having lunch in the same room. This resulted in background chatter and distractions from the simulation. We believe that this might have affected the focus and concentration of the participants. Since we cannot verify this effect, we discuss other factors that could have contributed to this difference: a matching surrounding, and possible artifacts in the visualization.

The first factor is also related to the different locations. The second group was able to use the simulation inside the operating room. The environment matched what they saw in the simulation. The second group had their operating table placed in a completely different environment: the break room. We believe this would make it more difficult for the participants to estimate what are dangerous and safe positions in the operating room. For example, if you would buy a couch in a store without measuring it, it would be difficult to imagine how the couch would fit in your living room. You would require a very good notion of size and scale. However, if you could see the couch in your living room, you would immediately be able to see how it would fit. We believe this to be similar to the visualization of the radiation patterns. If the table is visualized inside the correct room, the user can see where he or she should or should not stand during a procedure.

A second factor is the possible occurrence of artifacts during the simulation. The simulation has been tested inside an office environment, but the HoloLens showed anomalies in the crowded environment of the hospital. We believe there might have been artifacts in some visualizations of the first group. They could have reduced the accuracy of the simulation, such as moving the table to a different position. This would give the wrong radiation patterns in relation to the table. We cannot verify how often this occurred. After the first session, more testing was done and the second group had no artifacts. Before and after every participant, the simulation was checked. These two factors could have been the cause of the difference between the test results.

The question about the lead shield radiation reduction (question 2) had the lowest test results. Apparently the effect of the lead shielding was not clearly visible in the simulation. It shows a realistic radiation reduction, but this is not perceived as such by the users. This is mainly due to the three-dimensional visualization and the transparency of the lead shield. Users can see the radiation through the shield, so it is less obvious that the radiation is stopped. Also one participant stated: *"I found it difficult to remember the radiation patterns with lead shielding and compare it to the scene without. It might be useful to place both scenes next to each other."* In future editions of the visualization, it could help to exaggerate the visualization of radiation reduction more. The differences in radiation intensities might be too subtle. X-radiation is spread throughout an entire space, resulting in many moving particles. When visualizing the intensity changes too subtly, participants find it difficult to perceive any differences. This makes all positions inside the room look dangerous. This may be realistic, however the purpose of the application is also to inform users of less dangerous positions.

### 6.3.2 Part 2: Visualization, perceived learning effect and usability

The results from the questionnaire show that for 76% of the participants, the model confirmed the mental image they had of radiation patterns. As described in chapter 3, various visualization techniques were tested with a small group of participants in the hospital. All participants were in favor of the moving particles simulation. The results from figure 6.4a show that this preference scales to this larger user test. All participants responded very positively to the moving particles. Some made comments about the velocity of the moving particles or the meaning of the colors, but all agreed that it is an intuitive method to visualize X-radiation. Changes could be made to further improve the simulation. As with the learning effect, participants were not always able to clearly see the differences in radiation levels.

Additionally, 81% trusted that the visualized radiation model was reliable. Two participants asked what the underlying radiation model was and how it was validated. Due to the limited amount of time, we were not able to consult the participant that did not trust the radiation model to be reliable. The participant responded relatively neutral to almost all statements and did not find that the model confirmed his or her mental image.

### 6.3.3 Observations and comments

Even though interaction with the application through gestures has been reduced as much as possible, participants experienced difficulties. This is due to the unfamiliarity of the participants with the HoloLens. We believe that users will learn through experience. This was already noticeable with the two participants that had taken part in both user tests. They no longer experienced the difficulties they had the first time and even helped other participants interact with the HoloLens.

All participants immediately recognized the operating table and found it to be very realistic. During the user tests, most participants walked around the virtual objects instead of passing through them. They stated they had the feeling it was a solid object. From this we can conclude that the HoloLens creates a realistic simulation that can be used to simulate lifelike objects. We must note that the group inside the real operating room performed slightly better on the test. So even though a virtual object might be realistic, the simulation should match the surrounding area.

The heavy weight and the small field of view of the HoloLens were remarked upon by the participants. They found the Hololens (0.5 kg) to be heavy on their nose and forehead. Pressure on the nose can be reduced by adjusting the straps, but this requires practice. Additionally, the small field of view of the HoloLens surprised the participants. After walking through the simulation, they quickly adapted to this limited view. We believe that these disadvantages are hardware limitations that will be resolved in future editions of the HoloLens. Overall, all participants agreed that the headset is a suitable medium for the application. It provided them with a realistic three-dimensional image in the real world that could not have been created with a different medium.

## 6.4 Chapter conclusion

In this chapter we evaluated the learning effect and usability of the application with the target group. 21 employees of the Albert Schweitzer hospital tested the application on the HoloLens. With this research we evaluated the sub-questions:

- Q3: To what extent does the visualization lead to specialists and technologists having a better understanding of radiation patterns during a fluoroscopy?
- Q4: To what extent are the specialists and technologists better at identifying positions with high radiation doses inside the operating room during a fluoroscopy?

The test results evaluating Q4, showed that 20% of the participants improved their ability to identify positions with high radiation doses inside the operating room. Sub-question Q3 is assessed with the average results of the entire learning effect test. This shows that the application increased the understanding of radiation patterns during a fluoroscopy by 22,2% of the participants. The participants experienced a perceived learning effect of 66,7%. However on average for the overall test results, 15.9% of the participants worsened their test scores. Especially participants from the first group performed worse after using the application. We believe the different locations and the possible occurrence of artifacts might have influenced the test results and caused the difference between the two test groups. So due to the small number of participants and the large difference in test results between participants, we cannot not statistically confirm hypotheses H3 and H4. Nevertheless, the participants found the application valuable for training purposes and the HoloLens was deemed a suitable platform for visualizing radiation patterns in 3D.

# Chapter 7

# Conclusion and Future Work

## 7.1 Conclusion

Reducing radiation exposure and making personnel more aware of radiation patterns is an important objective for hospitals that use ionizing radiation. In this thesis, we evaluated the research question:

*How can mixed reality be used to simulate a radiation model that provides interventional cardiologists, radiologists and technologists with a better understanding of invisible three-dimensional radiation patterns?*

We assessed this question by developing an interactive application for the Microsoft HoloLens that visualizes the dose rate of three-dimensional X-rays inside an operating room. Using a real-time simulation of X-radiation, we calculated and visualized the rays during a fluoroscopy. Users can interact with the application and immediately see the changes in the visualization.

We formulated four sub-questions to further define the research. Q1 explored the preferred visualization technique by specialists and technologists for visualizing radiation dose rates. Since X-rays are invisible to the human eye, we developed a unique visualization method to visualize X-radiation. We first created four different visualization techniques that were tested and evaluated by seven employees of the Albert Schweitzer hospital. Circular particles moving through space were preferred by the participants and are used to visualize X-radiation which confirmed H1.

To verify Q2, we visually compared real radiation patterns to our model. Even though the radiation values could not be directly compared, we saw that the simulated patterns approach reality. Small errors could be solved by implementing more radiation interactions. Adding these features creates a more realistic model, however these changes may not always be visible in 3D. Care must be taken in preventing exaggerated effects. Medical physicists from the University Medical Center (UMC) Utrecht were impressed by the application and the HoloLens. They deemed the physics model adequate for this application and agreed with the methods that were used. Based on these results H2 was confirmed.

Finally, Q3 and Q4 evaluated the learning effect and usability of the application with the target group. 21 employees of the Albert Schweitzer hospital tested the application on the HoloLens. Our results showed that 20% of the participants performed better at

identifying unsafe positions inside the operating room, however 15.9% performed worse. Due to the limited availability of the operating rooms in the hospital, half of user tests were held in a crowded break room. We believed this might have influenced the test results and caused the difference between the two test groups. So due to the small number of participants and the difference in test results between participants, we could not statistically confirm hypotheses H3 and H4.

In conlusion, our scientific contribution is the use of holograms so interventional cardiologists, radiologists, and technologists get a better understanding of the radiation patterns in the operating room and become better at identifying positions with high radiation levels. To our knowledge, we are the first to have developed a fully stand-alone application that in real-time computes and simulates scatter radiation on a head-mounted mixed reality device. Others have explored the visualization of scatter radiation in the operating room using a two-dimensional hand-held screen (as described in section 2.5). Compared to their research, our system has the advantages that it does not require externally placed cameras and can be used to view radiation patterns in actual 3D, as each eye has a separate screen. Additionally, our research explored the possibilities of the HoloLens and found that mixed reality shows great promise for visualizing complex simulations such as ionizing radiation.

## 7.2 Future work

This thesis brought forward some interesting outcomes that deserve further research. For example, the results of the user test indicated that users become better at identifying dangerous position inside the operating room. However, the small number of participants limited statistical confirmation regarding a learning effect of the simulation. In future research, a larger test group should be used to determine the effect of the simulation on users and assess their understanding of radiation patterns.

Another interesting research area is the physics model behind the simulation. The simulation proved to show an accurate model of radiation patterns, but more radiation effects could be added such as Rayleigh scattering and Photoelectric effect. A study could be done to investigate the added value of more complex X-ray interactions when teaching radiation staff about three-dimensional radiation patterns.

After the completion of the application described in this thesis, Rodas et al. further developed their augmented reality application and applied it to the Microsoft HoloLens [56]. For future research the two applications could be compared and the advantages and limitations of both methods could be set side by side to further explore the use of mixed reality for visualizing scatter radiation.

Finally, additional visualization methods could help users identify positions with high radiation doses. The medical physicists from the University Medical Center Utrecht proposed the use of a two-dimensional heat map that represents the total radiation exposure visualized on the floor of the operating room (as described in section 5.2.3). Also gamification of the application could improve the overall user experience and help user remember the information better. Interactive sound and visual effects can make the user more aware radiation patterns and helpt decrease the amount of radiation they receive.

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# Appendix A

# X-radiation visualization

## A.1 Questionnaire

# Röntgen Visualisatie: Vragenlijst

**Huidige Functie** _____

**Aantal jaar ervaring in functie** _____

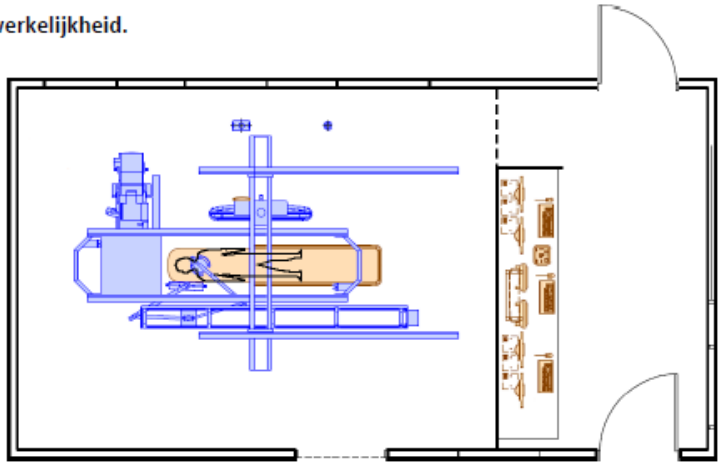
| | Oneens | | Neutraal | | Eens |
|---|---|---|---|---|---|
| De tweedimensionale visualisatie van de stralingsdosis heeft mij geholpen met het begrijpen van stralingspatronen. | 1 | 2 | 3 | 4 | 5 |
| Ik ben mij bewust van de stralingspatronen tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |
| Ik besteed tijd en aandacht aan de stralingsdosis die ik oploop tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |
| Ik denk dat een driedimensionale visualisatie mij een beter beeld kan geven van stralingspatronen tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |

Wie vangt er (van het personeel) tijdens een procedure de meeste straling op?

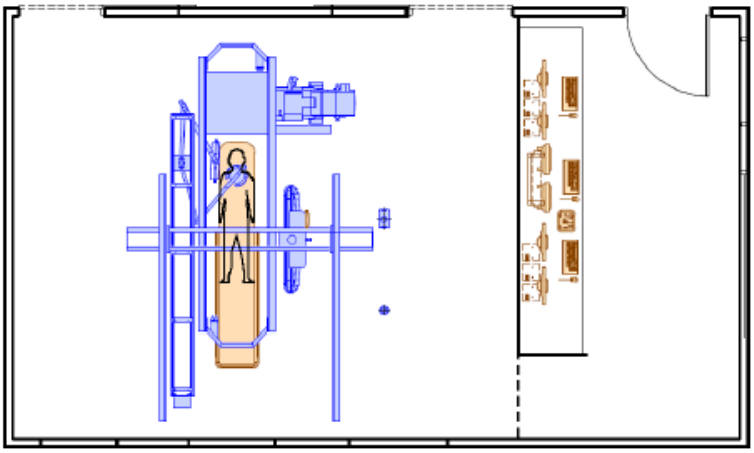
_____

1. **Geef op de onderstaande plattegronden aan waar u het meeste staat tijdens een procedure in de angio- of cathkamer met de C-boog aan.** Notitie: De plattegronden zijn benaderingen van de werkelijkheid.

**Cathkamer**



**Angiokamer**



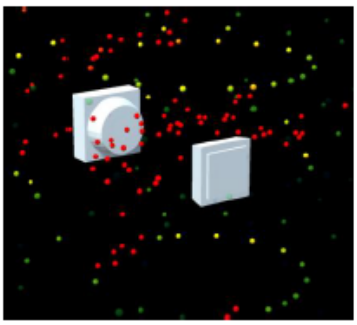
**2. Hoe zou u stralingspatronen visualiseren in 3D? Leg uit door middel van een schets.**

**Ga pas verder nadat u de HoloLens opgehad heeft.**

2

**3.** Geef voor ieder model aan in welke mate u het eens bent met de stellingen.

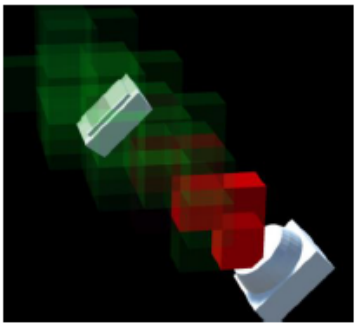
**STATISCH MODEL**



| Ik vind dat deze visualisatie... | Oneens | | Neutraal | | Eens |
|---|---|---|---|---|---|
| de straling duidelijk weergeeft. | 1 | 2 | 3 | 4 | 5 |
| aansluit bij mijn beeld van straling. | 1 | 2 | 3 | 4 | 5 |
| een betrouwbaar stralingsmodel zou kunnen weergeven. | 1 | 2 | 3 | 4 | 5 |
| ingezet zou kunnen worden voor trainingsdoeleinden. | 1 | 2 | 3 | 4 | 5 |
| duidelijker is met transparantie aan. | | | Ja / Nee | | |

Ik zou het volgende toevoegen/aanpassen aan deze visualisatie:

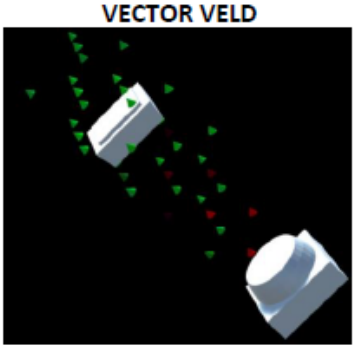
**VOXELS**



| Ik vind dat deze visualisatie... | Oneens | | Neutraal | | Eens |
|---|---|---|---|---|---|
| de straling duidelijk weergeeft. | 1 | 2 | 3 | 4 | 5 |
| aansluit bij mijn beeld van straling. | 1 | 2 | 3 | 4 | 5 |
| een betrouwbaar stralingsmodel zou kunnen weergeven. | 1 | 2 | 3 | 4 | 5 |
| ingezet zou kunnen worden voor trainingsdoeleinden. | 1 | 2 | 3 | 4 | 5 |
| duidelijker is met transparantie aan. | | | Ja / Nee | | |

Ik zou het volgende toevoegen/aanpassen aan deze visualisatie:

**VECTOR VELD**

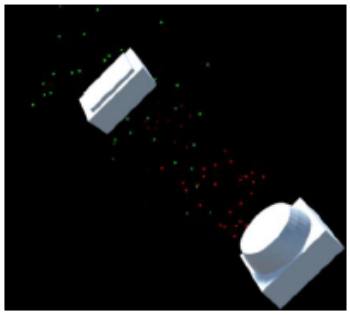


| Ik vind dat deze visualisatie... | Oneens | | Neutraal | | Eens |
|---|---|---|---|---|---|
| de straling duidelijk weergeeft. | 1 | 2 | 3 | 4 | 5 |
| aansluit bij mijn beeld van straling. | 1 | 2 | 3 | 4 | 5 |
| een betrouwbaar stralingsmodel zou kunnen weergeven. | 1 | 2 | 3 | 4 | 5 |
| ingezet zou kunnen worden voor trainingsdoeleinden. | 1 | 2 | 3 | 4 | 5 |
| duidelijker is met transparantie aan. | | | Ja / Nee | | |

Ik zou het volgende toevoegen/aanpassen aan deze visualisatie:

3

**BEWEGENDE DEELTJES**



| Ik vind dat deze visualisatie... | Oneens | | Neutraal | | Eens |
|---|---|---|---|---|---|
| de straling duidelijk weergeeft. | 1 | 2 | 3 | 4 | 5 |
| aansluit bij mijn beeld van straling. | 1 | 2 | 3 | 4 | 5 |
| een betrouwbaar stralingsmodel zou kunnen weergeven. | 1 | 2 | 3 | 4 | 5 |
| ingezet zou kunnen worden voor trainingsdoeleinden. | 1 | 2 | 3 | 4 | 5 |

Ik zou het volgende toevoegen/aanpassen aan deze visualisatie:

_____

_____

**4. Welke visualisaties vindt u het meest (en het minst) geschikt om straling te visualiseren? Nummer van 1 t/m 4, met 1 het meest geschikt.**

- ☐ Statisch model
- ☐ Voxels
- ☐ Vector veld
- ☐ Bewegende deeltjes

**5. Denkt u dat de HoloLens visualisaties ingezet kunnen worden voor trainingsdoeleinden om personeel meer bewust te maken van straling tijdens procedures? Waarom?**

_____

_____

_____

_____

**6. Zou u zelf de HoloLens willen gebruiken tijdens trainingen om straling te visualiseren? Of voldoet een ander medium (pc, tablet etc.)? Waarom?**

_____

_____

_____

_____

4

## A.2 Questions

1. Statisch model:
    - Wat vindt u van deze visualisatie?
2. Voxels:
    - Wat vindt u van deze visualisatie?
    - Vindt u het beter met of zonder transparantie? Waarom?
3. Vector veld:
    - Wat vindt u van deze visualisatie?
    - Wat vindt u van deze visualisatie vergeleken met de vorige (voxels)?
    - Vindt u het beter met of zonder transparantie? Waarom?
4. Bewegende deeltjes:
    - Wat vindt u van deze visualisatie?
    - Wat vindt u van deze visualisatie vergeleken met de vorige twee (voxels en vector veld)?
    - Van alle visualisaties, welke techniek vindt u het beste voor het visualiseren van Röntgen straling?

# Appendix B

# User tests

## B.1 Questionnaire

# Röntgen Visualisatie: Vragenlijst

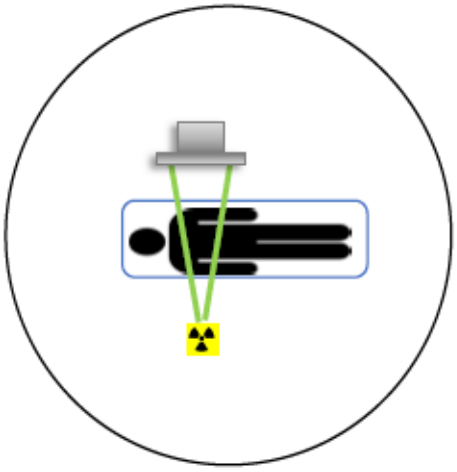
**Huidige Functie** _____

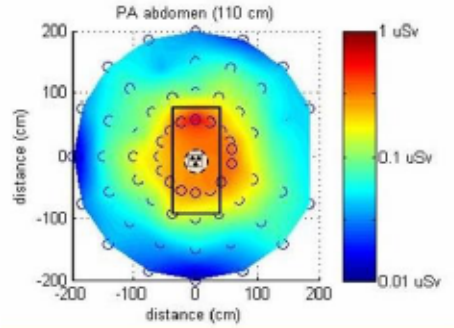
**Aantal jaar ervaring in functie** _____

**Kunt u alle kleuren goed waarnemen?** Ja / Nee, namelijk: _____

| **Huidige gebruik** | **Oneens** | | **Neutraal** | | **Eens** |
|---|---|---|---|---|---|
| Ik ben mij bewust van de stralingspatronen tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |
| Ik besteed tijd en aandacht aan de stralingsdosis die ik oploop tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |
| Ik denk dat een driedimensionale visualisatie mij een beter beeld kan geven van stralingspatronen tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |

1. **Bij een laterale positie van de C-arm kan ik het beste staan naast de:** stralingsbuis / detector
2. **De patiënt is de grootste bron van strooistraling:** Ja / Nee
3. **Goed geplaatste loodschermen kunnen de strooistraling verminderen met wel:** 10% / 50% / 90%
4. **Geef op de onderstaande afbeelding aan waar u denkt dat de meeste straling is tijdens een procedure met de C-boog in LAT positie. Zie rechter afbeelding voor een voorbeeld.**

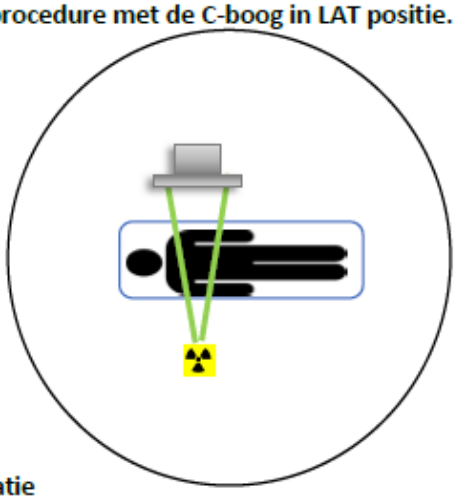


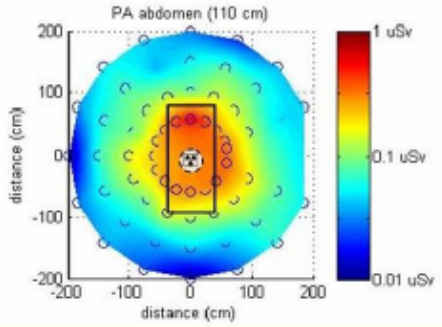



**Ga pas verder nadat u de HoloLens opgehad heeft.**

**Stralingspatronen**

1. **Bij een laterale positie van de C-arm kan ik het beste staan naast de:** stralingsbuis / detector
2. **De patiënt is de grootste bron van strooistraling:** Ja / Nee
3. **Goed geplaatste loodschermen kunnen de strooistraling verminderen met wel:** 10% / 50% / 90%
4. **Geef op de onderstaande afbeelding aan waar u denkt dat de meeste straling is tijdens een procedure met de C-boog in LAT positie. Zie rechter afbeelding voor een voorbeeld.**






| **Visualisatie** | **Oneens** | | **Neutraal** | | **Eens** |
|---|---|---|---|---|---|
| De visualisatie bevestigd mijn beeld van straling. | 1 | 2 | 3 | 4 | 5 |
| De visualisatie geeft een duidelijk beeld van stralingspatronen. | 1 | 2 | 3 | 4 | 5 |
| De visualisatie heeft mijn beeld van straling veranderd. | 1 | 2 | 3 | 4 | 5 |
| De stralingspatronen zijn in de visualisatie onduidelijk. | 1 | 2 | 3 | 4 | 5 |
| De visualisatie heeft mijn inzicht in stralingspatronen verbeterd. | 1 | 2 | 3 | 4 | 5 |
| Ik kan mij nu een beter beeld vormen van stralingspatronen tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |
| Ik geloof dat de visualisatie een betrouwbaar stralingsmodel weergeeft. | 1 | 2 | 3 | 4 | 5 |
| Ik zal door deze visualisatie meer tijd en aandacht besteden aan de stralingsdosis die ik oploop tijdens een procedure. | 1 | 2 | 3 | 4 | 5 |

| **Toepassing** | **Oneens** | | **Neutraal** | | **Eens** |
|---|---|---|---|---|---|
| Ik denk dat de visualisatie ingezet zou kunnen worden voor trainingsdoeleinden. | 1 | 2 | 3 | 4 | 5 |
| De huidige trainingsmethode is beter dan deze visualisatie. | 1 | 2 | 3 | 4 | 5 |
| Ik zou in de toekomst nieuwe versies van deze applicatie willen gebruiken voor training. | 1 | 2 | 3 | 4 | 5 |
| De HoloLens is een goede techniek om straling mee te visualiseren. | 1 | 2 | 3 | 4 | 5 |
| Ik zou liever een andere manier van visualisatie zien. Nee / Ja, namelijk: | | | | | |

## B.2 Questionnaire results

| | Correct both times | Improved | Wrong both times | Worsened |
|---|---|---|---|---|
| **1: Is the patient the largest scatter radiation source?** | 21 (100%) | 0 | 0 | 0 |
| **2: How much can lead screens reduce scatter radiation?** | 6 (28.6%) | 6 (28.6%) | 5 (23.8%) | 4 (19.0%) |
| **3: What is the best position to stand during LAT?** | 11 (52.4%) | 4 (19.0%) | 3 (14.3%) | 3 (14.3%) |
| **4: What is the most dangerous position to stand during LAT?** | 12 (57.1%) | 4 (19.0%) | 2 (9.5%) | 3 (14.3%) |

**(a)** Questionnaire results of **both groups** ($n = 21$).

| | Correct both times | Improved | Wrong both times | Worsened |
|---|---|---|---|---|
| **1: Is the patient the largest scatter radiation source?** | 9 (100%) | 0 | 0 | 0 |
| **2: How much can lead screens reduce scatter radiation?** | 3 (33.3%) | 2 (22.2%) | 3 (33.3%) | 1 (11.1%) |
| **3: What is the best position to stand during LAT?** | 3 (33.3%) | 0 | 3 (33.3%) | 3 (33.3%) |
| **4: What is the most dangerous position to stand during LAT?** | 4 (44.4%) | 1 (11.1%) | 2 (22.2%) | 2 (22.2%) |

**(b)** Questionnaire results of **the first group**, in the break room ($n = 9$).

| | Correct both times | Improved | Wrong both times | Worsened |
|---|---|---|---|---|
| **1: Is the patient the largest scatter radiation source?** | 12 (100%) | 0 | 0 | 0 |
| **2: How much can lead screens reduce scatter radiation?** | 3 (25%) | 4 (33.3%) | 2 (16.7%) | 3 (25%) |
| **3: What is the best position to stand during LAT?** | 8 (66.7%) | 4 (33.3%) | 0 | 0 |
| **4: What is the most dangerous position to stand during LAT?** | 8 (66.7%) | 3 (25%) | 0 | 1 (8.3%) |

**(c)** Questionnaire results of **the second group**, in the cardiac catheterization room ($n = 12$).

**Table B.1:** The comparison of the answers of 21 participants groups before and after using the application on the HoloLens about the learning effect. There were four possibilities: answering correct both times, answering correct only the second time, answering wrong both times, and answering wrong or worse the second time.

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| **1: The model confirms my image of radiation patterns.** | 0.0% | 4.8% | 9.5% | 47.6% | 28.6% |
| **2: The visualization provides a clear image of radiation patterns.** | 0.0% | 0.0% | 11.9% | 28.6% | 47.6% |
| **3: The visualized radiation patterns were unclear.** | 33.3% | 33.3% | 7.15% | 19.0% | 0.0% |
| **4: My image of radiation patterns has changed.** | 14.3% | 14.3% | 14.3% | 19.0% | 23.8% |
| **5: I trust the visualized radiation model is reliable.** | 0.0% | 4.8% | 7.15% | 61.9% | 19.0% |
| **6: My insight into radiation patterns has improved.** | 0.0% | 9.5% | 11.9% | 38.1% | 28.6% |
| **7: I can envision a better image of radiation patterns.** | 0.0% | 14.3% | 9.5% | 38.1% | 28.6% |
| **8: I will give more attention to the amount of radiation I receive.** | 9.5% | 4.8% | 14.3% | 38.1% | 19.0% |
| **9: The application could be used for training purposes.** | 0.0% | 4.8% | 0.0% | 19.0% | 76.2% |
| **10: The current training method in the hospital is better.** | 14.3% | 52.3% | 11.9% | 4.8% | 4.8% |
| **11: I would use new versions of this application for training.** | 0.0% | 0.0% | 7.15% | 38.1% | 47.6% |
| **12: The HoloLens is effective for this application.** | 0.0% | 0.0% | 0.0% | 42.9% | 57.1% |

**Table B.2:** Questionnaire results about the personal experience of 21 participants after using the application. A five-point Likert scale was used to measure how much they agreed or disagreed with 12 statements.