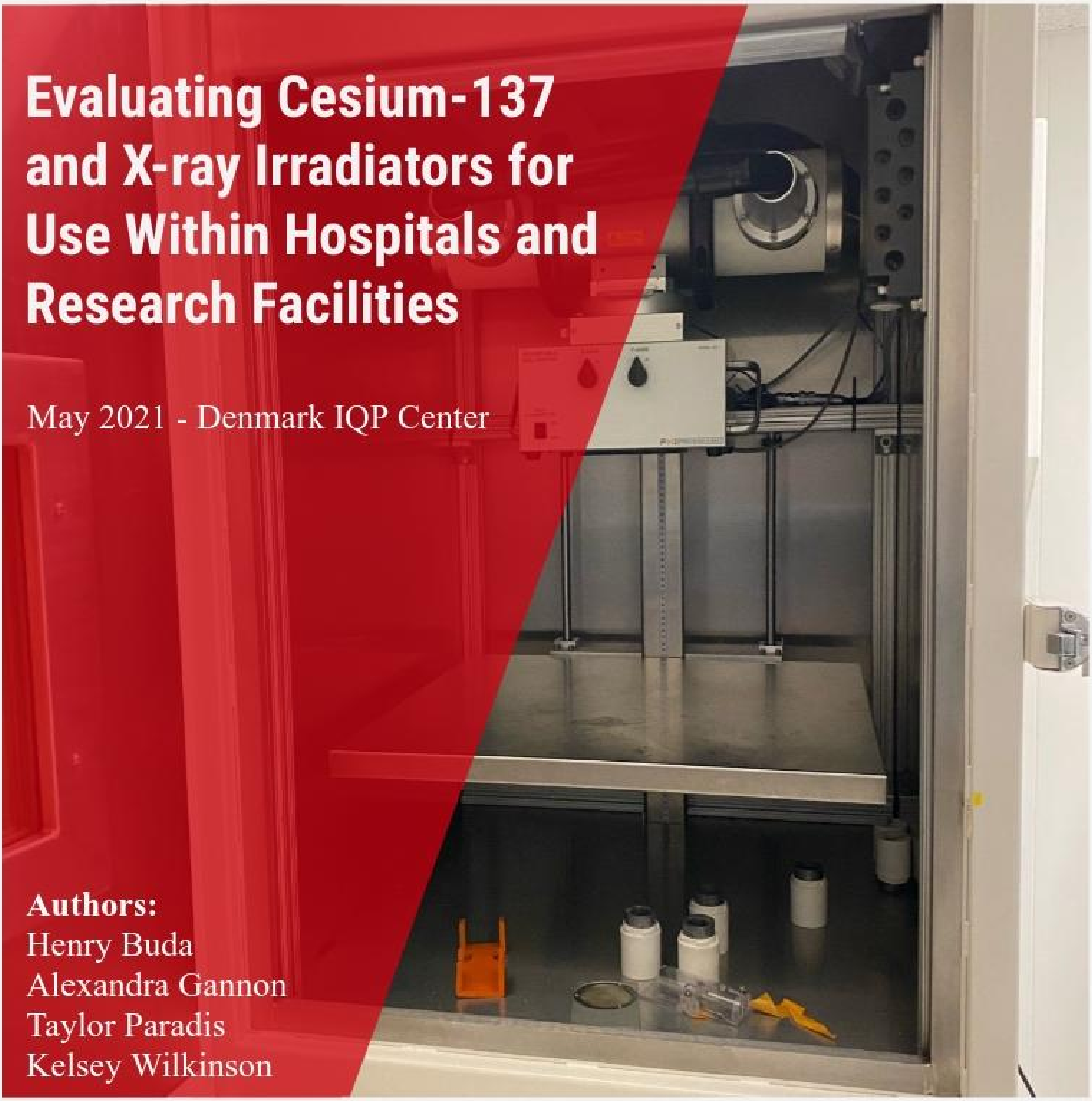

Evaluating Cesium-137 and X-ray Irradiators for Use Within Hospitals and Research Facilities

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Executive Summary

Introduction

Irradiation is the process by which an object is exposed to ionizing radiation resulting in desirable modifications. Currently, in the United States, there are approximately 800 irradiators in use, 550 of which are operated in hospitals for blood irradiation (Kramer, 2017). Our project focuses on the two most commonly used types of blood irradiators: Cesium-137 (Cs-137) and 320 kVp X-ray. The potential misuse of Cs-137 has raised concerns from the United States Department of Homeland Security and has prompted the National Research Council to commission studies on the replacement of Cs-137. A federal report by the Subcommittee on Nuclear Defense Research and Development included a small survey that only included 34 participants, all being either NIH or CDC employees. This small survey of professionals showed that 56% of people were either willing to make the change from Cesium to X-ray irradiators or were at least willing to test and then make the change if they were satisfied. The other 44% were unwilling to switch or try alternative technologies ("Transitioning from high-activity radioactive", 2016). The goal of our project was to conclude whether or not X-ray irradiation is a viable alternative to Cs-137 irradiation based on values obtained from simulations, as well as research into professionals' perspectives on a potential transition to X-ray irradiation technology.

Overview

Interviews with research groups and stand-alone irradiator users were conducted in order to obtain information pertaining to the efficiency of non-radioisotopic irradiators on a socioeconomic level. These interviews helped us develop questions for our administered surveys, which we used to poll users of irradiator technology on their reservations about making the switch from Cs-137 irradiators to X-ray irradiators. Monte Carlo N-particle Transport Code version 5 (MCNP5) was used to simulate the LET spectrum within a tissue equivalent model by modeling Cs-137 and 320 kVp X-ray irradiator sources. We were able to directly compare the delivered dose of each device in a simulated environment and determine how effective they are at providing the energy required to break down DNA. We then were able to identify which X-ray filters provide the best approximation of the Cs-137 LET spectrum.

Key Findings

We interviewed ten (10) individuals who have worked with Cs-137 and/or X-ray irradiators. These interviews consisted of professionals with different positions in the health physics field in order to obtain a large range of opinions. These interviews allowed the team to gain a stronger understanding of the social aspects surrounding the problems and concerns with the transition. We were able to explore the opinions of professionals who were successfully able to make the switch to non-radioisotopic irradiators, professionals who had problems arise while switching to non-radioisotopic irradiators, and professionals who haven't made the switch due to their concerns with non-radioisotopic irradiators. We were able to discuss the success that some professionals had and how they were able to achieve this success. Also, we were able to elicit concerns from our interviewees about this transition, many of which revolved around maintenance issues.

Based on the responses the team acquired through our interviews with health physics professionals, we were able to generate a survey that would allow members of the community to air their concerns regarding the switch while simultaneously collecting quantifiable data on subjects like the type of irradiators being used. The survey received thirty-five (35) responses from blood bank workers, Radiation Safety Officers, and researchers. Through the survey, we found that 28.6% of participants were fully willing to use X-rays as their sole irradiation source and the majority of participants were at least somewhat willing to solely use X-ray irradiators. Through the survey, we also discovered that our participants' major concerns with switching to 320 kVp X-ray irradiators were concerns with dose uniformity across a sample, the possibility that switching irradiators would interrupt projects in progress or invalidate existing research data, concerns with X-ray's accuracy, and the cost of transition.

Through our MCNP5 simulations, we determined that both types of irradiators are more than capable of delivering the energy required to destroy a T cell and its DNA. Our simulation results showed that X-rays had a higher LET compared to Cs-137 as they are able to deliver more energy per micron within the tissue model. We also discovered that a mixed filter was best at approximating the Cs-137 LET spectrum compared to the two other filter types tested in our simulation.

Conclusion

Our research indicates that switching to X-rays would not take away from the accuracy or quality of certain irradiation processes, and would benefit the medical community in terms of safety and security measures. While the process of transition can be challenging and may seem prohibitive to some, our survey and interview data suggest applying to government-funded programs can provide crucial aid in the transitional and removal process. Facilities and workers can also benefit from converting protocol so that it is compatible with the alternate technology, creating new safety and security protocol practice, and acquiring the training necessary to operate an X-ray irradiator which may vary from state to state.

Recommendations

We recommended that all hospitals and research facilities make the transition from Cs-137 to 320 kVp X-ray irradiators and utilize the resources, like the government-funded programs, to do so. A full list of our recommendations are listed below:

- Cesium irradiator replacement programs to dispose of Cs-137 irradiators and get up to half the cost of a new X-ray irradiator covered.
- Additional comparative studies should be performed on more specific uses of irradiation to resolve contradictions between published research papers.
- Government departments like the Office of Radiation Safety should ensure that replacement parts are available for X-ray irradiators given that they can require more maintenance than Cs-137 irradiators.
- All facilities utilizing X-ray irradiators should perform routine preliminary maintenance on X-ray irradiators to prevent breakdowns.

If facilities are unable, or unwilling, to discontinue the use of Cs-137 irradiators we suggest that every facility at least make a plan to make the transition to 320 kVp X-ray irradiators within the next decade.

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1. Introduction

Irradiation is the process by which an object is exposed to ionizing radiation resulting in desirable modifications. There are currently 800 irradiators active within the United States, with 550 being operated in hospitals and the remainder used for research purposes (Kramer, 2017). The most common source for blood irradiation is the radioactive isotope Cesium-137 (Cs-137), a product of nuclear fission between Uranium and Plutonium. Several catastrophic events such as the Goiana Cesium Incident have led to security concerns from the general public which lead to Congress passing the John S. McCain National Defense Authorization Act (NDAA) which set a goal to eliminate the use of blood irradiation devices that rely on Cesium chloride by December 2027. This has led to an increased demand for a viable safer alternative to current methods of irradiation ("Transitioning from high-activity radioactive", 2016).

320 kVp X-ray irradiators have been proposed as an alternative to Cs-137, but researchers maintain reservations about the ability of X-rays to produce results of the same quality. A small survey conducted by the Subcommittee on Nuclear Defense Research and Development showed that 56% of researchers were willing to switch from Cs-137 to 320 kVp X-ray irradiators while the other 44% were unwilling to try the alternative technologies ("Transitioning from high-activity radioactive", 2016). This has led to many hospitals and research facilities around the United States maintaining active security programs for their Cs-137 sources, a potential security concern for the general public.

The goal of our project was to evaluate whether X-ray irradiation is a viable alternative to Cs-137 irradiation based on values obtained from Monte Carlo simulations. We began by obtaining energy spectrum values for both 320 kVp and Cs-137 source types and used MCNP5 simulation software to evaluate absorbed dose through different X-ray filters. We used the results from this comparison to suggest X-ray irradiation implementation for all relevant projects that use Cs-137 irradiators. We then conducted formal interviews with research groups, stand-alone researchers, and medical practitioners to gain a better understanding of the societal objections and approvals surrounding the switch. A survey with thirty-five (35) participants was also conducted to further understand these societal opinions. After analyzing our survey and interview results, we framed our findings in a way that directly addresses the concerns of those opposed to a transition to X-ray irradiation. Using these methods, our group aimed to conclude whether or not X-ray irradiation is a viable alternative to Cs-137 irradiation and if so, help encourage this switch to non-radioisotopic irradiators.

2. Literature Review

2.1 Introduction to Irradiation

The role of irradiators in hospitals is to deactivate T lymphocytes, also known as T cells, a common and important immunoregulatory cell. Irradiating T cells causes damage to their DNA and prevents them from attacking the host after a blood transfusion, which would result in a condition known as transfusion-associated graft-versus-host disease (TV-GVHD). This condition is characterized by immune cells (introduced through transfusion) attacking the immune system of a healthy individual. Normally, if any remaining transfused cells are present they are either small in number or are found and destroyed by the host immune system after a period of discomfort. Immunocompromised individuals are especially at risk for this type of incident because of their naturally occurring low levels of T lymphocytes (Moroff & Luban, 1997). Red blood cells are only mildly affected by this process since they do not contain a nucleus that can be disrupted by radiation. Instead, the radiation interacts with the potassium channels present in the cell membrane causing potassium leakage out of the cell. This is not an issue within the body and can be easily fixed but it does decrease the shelf life of irradiated blood (“Effects of ionizing radiation on blood and blood components: A survey”, 1997).

While irradiators are widely used in the medical industry, it is not their only application. Another common use of irradiation technology is for the sterilization of single-use medical devices. Similar to T lymphocytes, bacteria and viral contaminants are severely damaged by radiation. This is why irradiation is also an approved method for handling a variety of food imports. Meats such as beef, pork, crustaceans, and mollusks can all be irradiated to eliminate food-borne illnesses when entering the country. In addition, sprouts and seeds that enter the country can also be irradiated to delay the sprouting process or to eliminate various types of potentially harmful insects without using pesticides (Farkas & Mohácsi-Farkas, 2011).

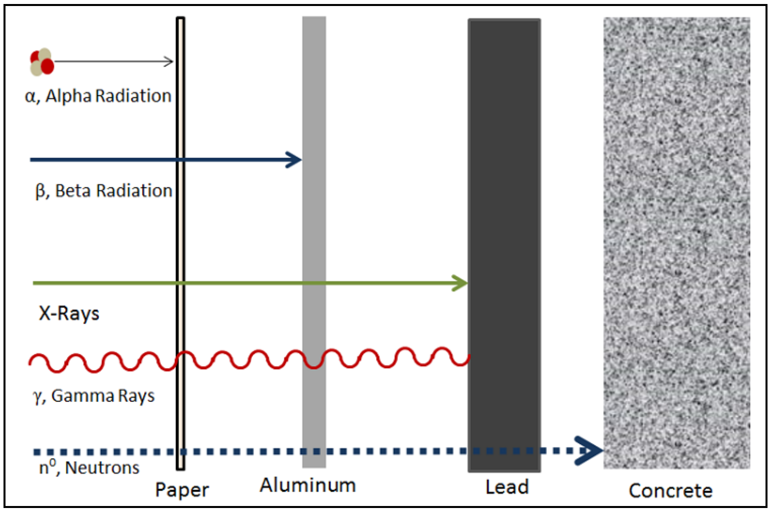

Figure 1: Penetration levels of different products of decay, with similar penetration from X-rays and Gamma Rays (Hanania, 2017).

Our project focuses on the two commonly used types of blood irradiators. The first type uses the radioactive decay of Cesium 137 (Cs-137) to produce gamma rays. The second type uses electricity to produce X-rays. Despite having different names, gamma rays and X-rays are similar to each other in a variety of ways such as their interactions with matter which can be seen in Figure 1. Both waves are the result of photons that originate in different parts of the electromagnetic spectrum, the main difference between the two is energy. Gamma rays are the result of radioactive decay and originate from the nucleus of an atom, while X-rays originate from the electrons surrounding the nucleus after they receive enough energy to break free of their electron shells. There are two main ways these photons interact with the tissues of our bodies; the photoelectric effect and Compton scattering, which can be seen in Figure 2 below. The photoelectric effect occurs when incoming radiation hits electrons found in the molecules of our bodies and gives them enough energy to break free of their electron shell. This new electron travels for a couple of millimeters in the body before losing its energy. The second interaction, called Compton scattering, occurs when the incoming radiation gives the electron more energy than it can carry kinetically, which forces it to eject some of the excess energy as a lower energy photon. These photons can vary in energy depending on the initial ray that created them. If the energy is high enough, the photon can then carry out another Compton scattering event or a photoelectric effect on a nearby atom which causes the radiation dose to rise above predicted levels (Klassen, 2011).

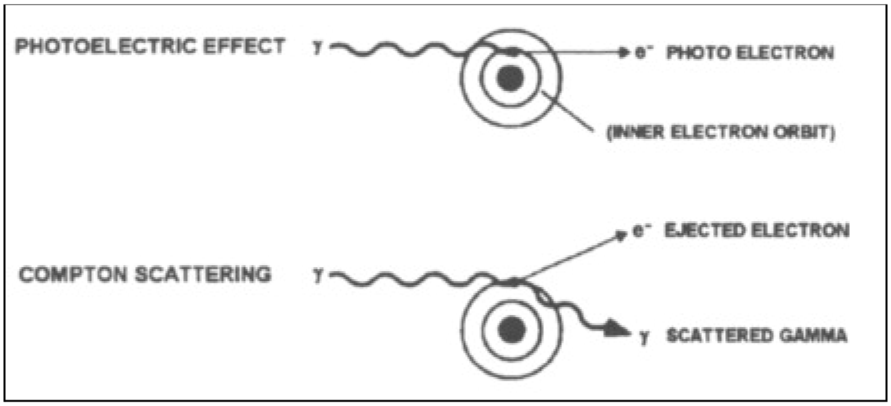

Figure 2: Photoelectric Effect vs. Compton Scattering (Coppin & Rydberg, 2002).

2.1.1 Introduction to Types of Irradiators

A Cs-137 based blood irradiator consists of a rotating turntable in which the blood components are placed which can be seen in part A of Figure 3 below. Around the spinning turntable are anywhere from one to four pencil sources of Cs-137. The exact arrangement and number of these rods will vary depending on both the machine and the client's needs. Rotating the blood components during the irradiation process is useful for ensuring an accurate and uniform dose. The turntable and pencil source is enclosed with a lead shielding that provides shielding for operator safety ((Moroff & Luban, 1997).

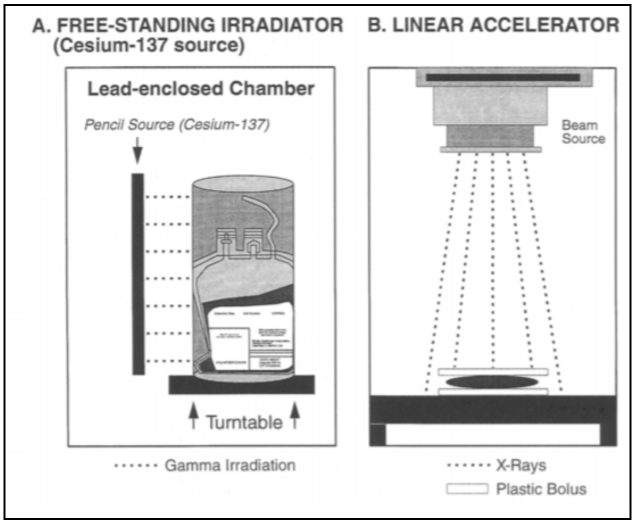

Figure 3: Free-standing Cs-137 irradiator vs 320 kVp X-ray irradiator (Moroff & Luban, 1997).

An X-ray-based blood irradiator is composed of a metal source above a plate which can be seen in part B of Figure 3 above. The metal source is bombarded with electrons that are given energy through a linear accelerator that accelerates charged particles down a path towards a target using electromagnets. These high-energy electrons cause the release of X-rays as they hit the metal source. The blood is placed below the metal source between two plastic sheets, the first plastic sheet is designed to allow the X-rays to easily pass through while attenuating their energy to the desired levels. The second plastic sheet is placed below the blood and is designed to promote 180-degree deflection of X-rays known as backscattering. This sends the X-rays back into the blood components which increases the homogeneity of the sample (Moroff & Luban, 1997).

2.2 Cesium-137

Cesium-137 is a popular radioactive isotope that has been used in the medical field for decades, particularly for the calibration of radiation-detection equipment, medical radiation therapy, and sterilization purposes. The radionuclide can be found in countries throughout the world such as Russia, India, and China, but is a staple for blood irradiation in the United States. It is a product of nuclear fission between Uranium and Plutonium and has a half-life of approximately 30 years, making it an ideal candidate for long lasting radiation. However, this half-life is also what makes this product so dangerous (Goudarzi, 2021).

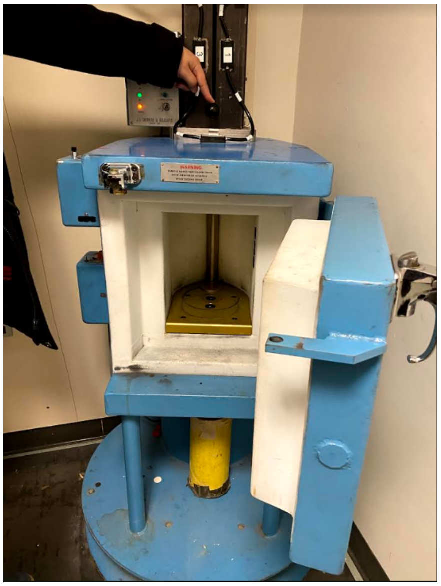

Figure 4: Cesium-137 irradiator at Massachusetts General Hospital.

Several nations have moved entirely away from Cs-137 irradiator devices after a series of catastrophic incidents involving the release of radiation. Some of the most notable exposures include Chernobyl, the Goiana Cesium Incident, and the Fukushima Daiichi accident. Figure 4 shows a Cesium irradiator similar to the one from the incident that took place in Washington, DC in 2019. In addition to the immediate danger of radiation exposure, these disasters also provided long-term effects on the surrounding environment. A large security threat for the U.S. is the potential of terrorism using Cs-137 since Cesium can be transformed into aerosol form (Kamen, 2019). The same isotopes used for the Cs-137 irradiators that can be found in hospitals and research labs can be used to build a dirty bomb, a radiological dispersal device created by combining the radioactive material with conventional explosives (like dynamite). Dirty bombs release radiation when they explode; they also contaminate property, require costly cleanup, and overall can create a lot of fear & panic (“Backgrounder on dirty bombs", 2018*)*.

In light of this, Norway & France have successfully eliminated all Cs-137 irradiators in 2015 and 2016 respectively and Japan has removed 8% of theirs as of 2010. (Kamen, 2019) Furthermore, the potential misuse of Cs-137 has raised several concerns from the US Department of Homeland Security and has prompted the National Research Council to commission studies replacing Cs-137. As stated, the John S. McCain National Defense Authorization Act aims to eliminate the use of Cesium-based blood irradiators by 2027. Several smaller programs in the US have already taken steps to switch over to non-radioisotopic alternatives to eliminate the risk of dirty bombs. In 2017, the New York City Department of Health and Mental Hygiene announced a program to replace high-activity radioactive sources in hospitals, medical facilities, and blood banks all throughout New York. In 2018, Mount Sinai Medical Center successfully disposed of all their Cs-137 irradiators that were used for research and blood irradiation with X-ray technology. Mount Sinai Medical Center states that the X-ray blood irradiators are superior in capability and can irradiate blood bags in less than half the time compared to their Cs-137 irradiators ("Replacing Cesium-137 irradiators", 2018). This project aims to evaluate the risks, benefits, and potential costs associated with Cs-137 irradiators compared with 320 kVp X-ray irradiators.

2.3 X-ray Irradiators

According to The Department of Homeland Security, 320 kVp X-ray irradiators have emerged as one of the best possible options for replacing Cs-137 in the medical field, as it is affordable, effective, and requires much fewer security methods compared to its Cesium counterpart. Though these devices were brought to the market relatively recently (about 20 years), there is evidence to suggest that many are satisfied with the alternative method ("Transitioning from high-activity radioactive", 2016). Figure 5 shows one type of 320 kVp X-ray irradiator used at Massachusetts General Hospital.

Figure 5: 320 kVp X-ray at Massachusetts General Hospital.

320 kVp X-ray irradiators produce photons with similar energy ranges to gamma rays through a process known as Bremsstrahlung. Bremsstrahlung is the radiation given off by free electrons getting deflected while passing through matter in strong electric fields of atomic nuclei (Stacey & Vestrand, 2001). This proposal focuses primarily on 320 kVp X-ray irradiators, 'kVp' referring to the kilovoltage peak applied to the X-ray tube. As seen in Figure 6 below, electrons accelerate from the cathode to the anode based on the tube voltage which determines the quantity and quality of the photons generated. In other words, 320 is the highest voltage that will be produced by the X-ray irradiator during exposure (Murphy & Goel, 2020).

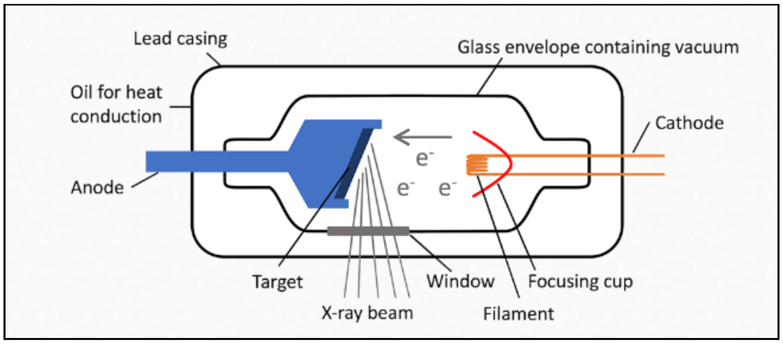

Figure 6: Diagram of an X-ray irradiator (Abdulla, 2020).

X-ray filters are used to attenuate low-energy photons from the spectrum. This can be achieved by placing metal sheets in the X-ray beam before it reaches the target. These filters are used to protect patients from absorbing low-energy photons. Filtration reduces the intensity of the X-rays by removing lower energy photons from the polychromatic beam. The attenuation properties of the filter do not affect the higher energy X-rays within a beam spectrum, meaning it won't alter the desired results. There are two main types of filters: built-in filters and filters that are added by the users. The built-in filters primarily are from components in the X-ray tube like the window, housing, and cooling oil. These components of the X-ray tubes contribute to the filtration of the rays by design and they contribute around 0.5-1.0 mm aluminum (Al). US guidelines state that there is a minimum of 2.5 mm of Al filtration for X-rays operating above 70 kVp (Murphy & Goel, n.d.). A study was successfully able to use 320 kVp X-ray irradiation to meet their standards, as it was able to provide similar results to their Cs-137 irradiator. This study utilized a filter comprising 0.75 mm tin, 0.25mm copper, 1.5 mm aluminum, and a half-value layer of 3.7mm copper (Gott, 2020). Figure 7 below shows two different types of filters used in 320 kVp X-ray irradiators.

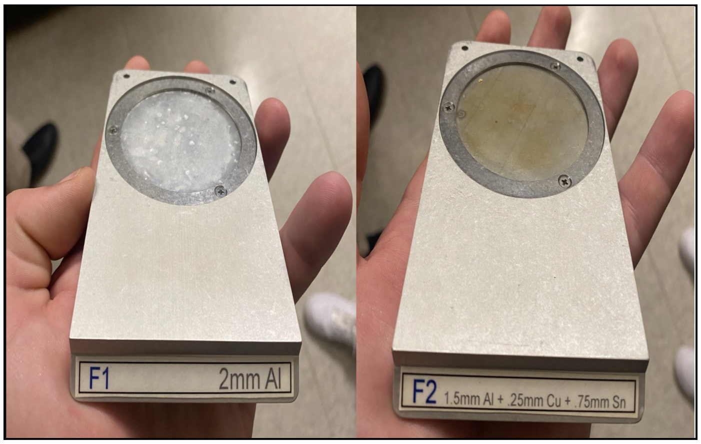

Figure 7: X-ray filters from Massachusetts General Hospital. Image on left is 2mm Aluminum and image on right is 1.5mm Aluminum + .25mm Copper, and .75 mm Tin.

Some of the most notable issues documented with the implementation of the newer X-ray models include elaborate plumbing, cooling requirements, effectiveness, and frequent breakdowns, but the National Nuclear Security Administration is currently funding research to develop flat-panel X-ray sources for blood irradiation. These new models will weigh between

200 and 500 pounds, operate on 110 AC power, and are expected to be extremely reliable (“Transitioning from high-activity radioactive”, 2016).

2.4 Cs-137 and 320 kVp X-ray Comparison

A federal report from 2016 by the Subcommittee on Nuclear Defense Research and Development with the National Science and Technology Council discussed the possibility of replacing Cs-137 irradiators. It stated that the current state of research on irradiation proves that, for irradiation on mammalian cells and small animals such as mice, X-ray irradiation proves to be an adequate alternative to Cesium. In the terms of radio-resistant organisms and larger animals, like bacteria and rats, the X-ray irradiators did not perform as well as the Cs-137 irradiators (“Transitioning from high-activity radioactive”, 2016). The federal report didn’t elaborate any more on their findings, but this research sparked many further studies.

In a 2020 study, Katherine Gott compared different methods of irradiation in a mouse bone marrow transplant model which is shown in Figure 8. Her team used a Gammacell-1000 Unite which utilizes Cs-137 radiation secured within a biological lead shield. This machine emitted 662-keV gamma-ray photons. When the photons penetrate the source, a spectrum of photon energies arise which exposes the irradiated targets. The other irradiator her team used was the X-RAD 320 Unit which uses a cathode generator (specifically the GE ISOVOLT 320 TITAN X-ray Unit) with a power electronics module and anode generator. These generate negative and positive high voltages which are used to generate photons of keV energies. An oil-to-air cooling system was used for the X-RAD 320 Unit. They conducted a study on bone marrow chimeric mice to determine if the X-RAD 320 irradiator would be a good alternative due to the concerns of homeland security. Their main concern was that the X-RAD 320 irradiator X-rays wouldn’t have a high enough energy for tissue penetration that would allow for a successful bone marrow transplant and this was proven in their study. There were still a significant amount of splenocytes (a type of white blood cell) remaining after the X-ray irradiation. The researchers suggest that higher doses should be researched (Gott, 2020).

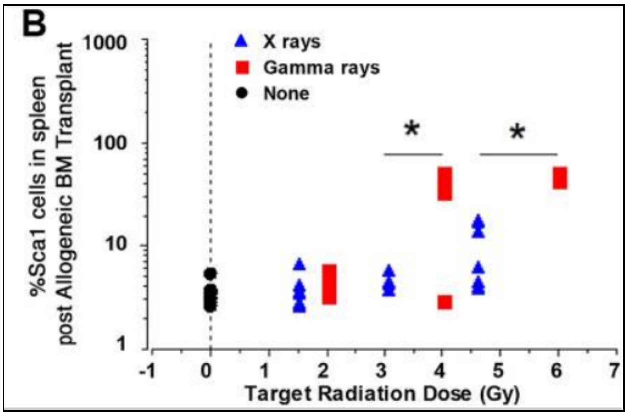

Figure 8: A chart from Gott's study showing that the %Sca1 cells (representing reconstruction) after Cs-137 irradiator & X-ray Irradiation doses (Gott, 2020).

Anna Andersen's (2020) comparative study of the two irradiation methods yielded more promising results. This study compared 350 kV X-ray and Cs-137 doses on immunodeficient mice prior to human stem cell transplantation. The irradiators that were used for this experiment were a Gammacelle 2000 RH Cs-137 irradiator and a MultiRad350 X-RAD 350 kV X-ray irradiator, using a Thoraeus filter to minimize unwanted low-energy photons. There were no significant differences between dose measurements of the different types of irradiators. They were able to use both methods to successfully surgically remove the mouse bone marrow, allowing for the human stem cell engraftment and encouraging the transition to X-ray-based sources (Andersen, 2020).

Though there are many studies to consider concerning the efficiency of X-ray irradiators compared to Cs-137 irradiators, we must also consider what effects switching to X-ray irradiators will have on the general public, and the stakeholders involved in these transitions.

2.5 Social Aspects

Ensuring that the 320 kVp X-ray irradiators are the best replacements for the current irradiation methods is a large portion of the research, but the social aspect is especially crucial to this project. The elimination of Cs-137 irradiators has been successfully carried out in other countries and like previously stated, the U.S aims to cease the use of them by 2027 as there are other viable options. However, a significant number of people positioned to carry out this transmission disapprove of the switch to X-ray irradiators. Our study examined the concerns that those who oppose the switch to X-ray irradiators have, as well as the success that others have had with the transition.

2.5.1 Professional Concerns with Alternatives

There are several points of contention from professionals concerning the transition from Cs-137 irradiators to X-ray irradiators that should be both clearly established and addressed when recommending the switch. Certain facilities are worried about the expense of safely removing their cesium irradiators, purchasing the X-ray irradiators, and providing maintenance for these X-ray irradiators. Operators of X-ray irradiators are not required to undergo as intensive background checks as are their Cs-137 counterparts, a process which can take several months to complete. X-ray irradiators do require more power to operate and will require more maintenance and replacements than the Cs-137 irradiators, which can operate for 30 years with few problems (Illiopulos, 2018). The interruption of in-process research projects also proves to be an area of opposition from those who have research projects that utilize Cs-137. Research projects that have been operating for multiple years and have Cs-137 irradiators written into their protocol are unable to switch to X-ray irradiators, which have a much smaller energy spectrum, without repercussions on their data. Completely switching to alternative irradiator sources also means that the results of past research utilizing Cs-137 could no longer be scientifically replicable (Borchardt, 2008). Other reasons for hesitation generally include dose uniformity concerns and accuracy issues.

These concerns have moved many professionals who use irradiators to come forward and make their concerns about switching to alternatives public. An example of this is a letter from Dr. Abba Zubair of the Mayo Clinic sent to the U.S. Nuclear Regulatory Commission stating concerns that he and his colleagues had about this issue. Zubair expressed concerns with the cost of replacing all of the Cs-137 irradiators; he stated that they would create hardship both for hospitals and blood banks. He believed that if this change is forced, the government should provide funding for the removal of the Cs-137 blood bank irradiators. He also mentioned that X-ray blood irradiators are not as efficient or reliable as current ones and that they are associated with a higher cost for maintenance, but it should be noted that this statement is over a decade old from 2008. Zubair stated the Cs-137 irradiators are more reliable and efficient compared to other blood irradiators and believed that since blood banks are staffed 24 hours a day, 7 days a week, along with increased security, that the Cs-137 irradiators are sufficiently secured. He made another valid point that if these changes were to be made, that a sufficient amount of time should be given in order to replace the blood irradiators. It can take months to receive an X-ray blood irradiator due to the capability of U.S. manufacturing and the number of irradiators that would have to be replaced. If Cs-137 irradiators are outlawed before hospitals and blood banks are able to receive an X-ray blood irradiator this could affect patient care (Zubair 2008). Zubair is a good representation of the transfusion medicine community and his arguments are paradigmatic of a significant line of opposition among healthcare providers.

A federal report by the Subcommittee on Nuclear Defense Research and Development included a small survey that included 34 employees from either NIH or the CDC. This small survey of professionals showed that 56% of people were either willing to make the change from Cesium to X-ray irradiators or were at least willing to test and then make the change if they were satisfied. The other 44% were unwilling to switch or try the alternative technologies ("Transitioning from high-activity radioactive", 2016).

Through networking, while distributing our survey, a local radiation safety officer reached out to our Sponsor to share a survey similar to ours. We were able to receive an additional one-hundred-six (106) responses intended to gauge the researcher's interest in switching to X-ray irradiators. Utilizing this survey and the above survey mentioned, we were able to enhance the format of our own survey and compare responses ("National Institutes of Health (NIT) survey results about Cs-137 & X-ray irradiators", 2021).

2.5.2 Government Agendas

In order to make this switch more acceptable to those who would be affected the report mentions four methods that different agencies could take. The first is a federal procurement or grant-making approach which would include grant programs to conduct clinical trials and put internal protocols in place to phase out the use of the existing devices. The regulatory priorities approach would not involve direct funding of the new devices, but it would support and promote information about the phase-out of Cesium irradiators. The education and outreach approach would have agencies support and share the information on alternative methods to

Cesium, provide training on non-Cesium-based irradiation, and would lead by example for the user community. The final approach is research and development, which would involve many agencies all responsible for supporting the research in utilizing the different irradiators. These agencies will provide information to support the change to non-Cesium-based irradiation, publish their findings, and make statements that support a transition to the alternative technology ("Transitioning from high-activity radioactive", 2016). Significant progress has been made in multiples of these approaches, but most notable is the education and outreach approach and the federal procurement approach through programs like CIRP (Cesium Irradiator Replacement Program).

The Cesium Irradiator Replacement Project was created to reduce the risk of radiological material in the U.S. by the U.S. Department of Energy National Nuclear Security Administration Office of Radiological Security. This program encourages the switch to alternative technologies in order to reduce risk and is completely voluntary unlike some European countries (ie. Norway and France) who made this switch to alternatives mandatory. This program provides outreach and education to organizations that use radioisotopic devices to stimulate interest in alternatives. As of February 2020, this program has successfully eliminated 83 cesium and cobalt devices (Lieberman & Itamura, 2020). This program will remove and dispose of Cs-137 irradiators for the facility which would typically cost between \$100 - \$200k per irradiator. This program will also provide financial aid towards the payment of a non-radioisotopic irradiator (up to 50% of the cost) as well as training, maintenance, and spare part costs (Office of Radiological Security, 2018).

In order to make the switch from Cs-137 to X-ray irradiators, further research needs to be done and collected and the right steps need to be taken in making the change over possible in hospitals and blood banks. By demonstrating the efficiency of X-ray irradiators and exploring factors in practitioners' adoption of this safer technology the team aims to aid with this switch.

3. Methodology

3.1 Introduction

Our team worked with Dr. Matthew Carey, Senior Health Physicist in Environmental Health and Safety at Harvard University, to establish and publish evidence that X-ray irradiators are a viable alternative to Cs-137 irradiators in hopes of appealing to concerns expressed by researchers in the community. Our research pursued three objectives that allowed us to consider the mechanical, institutional, and broader social dimensions that affect the transition to this new technology.

3.2 Objective Overview

1. Identify methods to encourage hospitals and research facilities to switch from Cs-137 to 320 kVp X-ray irradiators
2. Use Monte-Carlo based radiation simulation MCNP5 to compare Cs-137 and 320 kVp X-ray irradiators
3. Identify which X-ray filters provide the best approximation of the Cs-137 LET spectrum

3.3 Objective 1

Our first objective was to identify existing methods already in progress used to switch from Cs-137 irradiators to X-ray irradiators. In addition, we will identify incentives used to encourage facility participation in existing Cs-137 exchange programs, making the switch from Cs-137 to 320 kVp X-ray irradiators. This project gauged professionals' perspectives on the cost of replacement, the learning curve of the new method, and whether the 320 kVp X-rays are efficient and accurate alternatives.

3.3.1 What Methodology will be Used

We conducted ten (10) interviews with professionals in medical and research fields to understand contemporary perspectives surrounding X-ray transition programs. This included doctors, employees in radiation safety, and research facilities that use Cs-137 irradiators. We also administered a survey to professionals with experience using Cs-137 sources (and received

35 responses) to gain a better perspective on how to improve existing Cs-137 exchange programs. These interviews and our survey provided us with opinions of multiple professionals whose perspectives will inform our recommendations for optimizing a transition to X-ray-based irradiators.

3.3.2 How Data will be Acquired and Analyzed

The team interviewed ten (10) professionals with experience using Cs-137 and X-ray irradiators, ranging from doctors to individual researchers. We inquired about their opinions on Cs-137 and X-ray-based irradiators as well as their experiences and uses for both types of irradiators. We then discussed concerns they may have about either type of irradiator and their willingness to switch with X-ray irradiators (see appendix A). We compared the information provided from all of our interviews to understand key concerns that the majority of our interviewees had about the acceptance of this new technology of 320 kVp X-rays. The team also created a survey (see appendix C) to gain the perspectives of thirty-five (35) other professionals in this field. The survey was formatted very similarly to our interviews but would allow us to reach a larger population. We asked our sponsor and those we interviewed to help distribute the survey to other professionals.

Interviews were conducted virtually due to the Covid-19 pandemic. We asked those who we are interviewing if they consent to us recording our meeting, producing a full transcript. Survey data were recorded and saved in order for further observation and analysis. Data collected between interviews and surveys provided a basis for developing methods to encourage an equitable switch to X-ray irradiators. Common issues that professionals have were researched in order to determine if these individuals could benefit from switching their irradiator.

3.3.3 Why this Methodology Achieved our Goals

Based on our literature review, the team was able to predict problems that may arise in switching from Cs-137 to X-ray irradiation. Interviews and surveys (Appendix A & Appendix C) allowed us to understand the perspectives of professionals who work with irradiator technology. With the information gathered, the team worked to create methods and protocols to address the concerns shared by professionals, so as to facilitate the switch to non-radioisotopic irradiators.

3.4 Objective 2

Next, we used Monte-Carlo-based radiation transport code, MCNP5, to simulate the (LET) spectrum at the cellular level for both a Cs-137 source and a 320 kVp X-ray source.

3.4.1 What Methodology will be Used

We used MCNP5 to simulate the LET in a tissue-equivalent (TE) model using both Cs-137 and 320 kVp X-ray irradiator sources. The Monte Carlo method, which uses repeated random sampling, was used to simulate photon transport (Andreo, 2018). The simulated sources were placed at 10 centimeters from a tissue equivalent model. Normally in an irradiator, the distance from the source is highly variable as many irradiators have moving or rotating platforms that allow them to be versatile for many different sample types. Due to this, we found it more important to keep the distance from the source consistent across all trials rather than trying to put the source at a scale away from the irradiator. From this model, we modeled the photon's interactions with the surface of our model and collected LET information about the emitted electrons that go deeper into our model.

3.4.2 How Data will be Acquired and Analyzed

A basic geometry, represented in Figure 9, was used for the simulation to mimic the environment of the irradiator. It included the irradiation source enclosed in a case, the filter, and the target being irradiated. Our codes required a random element to model radiation. Due to this, the simulator was run multiple times in order to eliminate random errors from our data. Data was recorded in text documents that required additional processing to gather useful information. Once the data was looked through it was entered into an Excel sheet in order to convert to the appropriate units. The simulations were run at photon counts of over 1*10^9 in order to eliminate uncertainty and random error in our simulations.

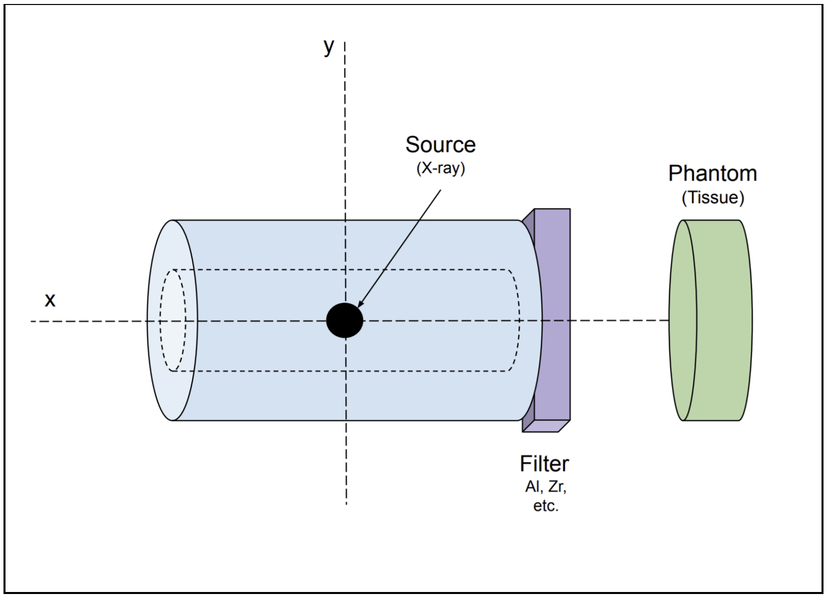

Figure 9: Simulation software basic geometry.

3.4.3 Why this Methodology Achieved our Goals

By doing this, we were able to directly compare the delivered dose of each device in a simulated environment and determine how effective they are at providing the energy required to break down DNA. The team also used the program Visual Editor to create graphical representations on the performance of both types of irradiators. The images obtained, including the one shown in Figure 10, provided a good way for the reader to visualize our concepts and understand the way that the software simulates both 320 kVp X-rays and Cs-137.

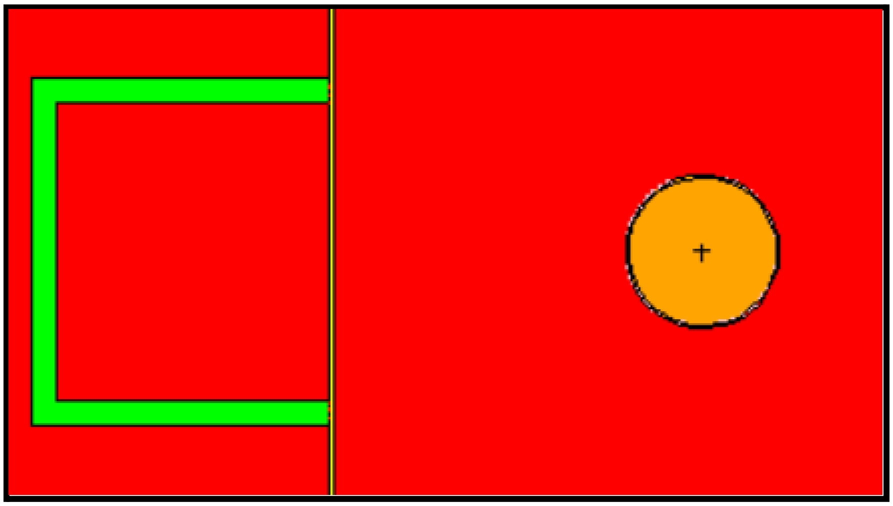

Figure 10: View of geometry within the Visual Editor software.

3.5 Objective 3

Our third objective was to identify which X-ray filters provide the best approximation of the Cs-137 LET spectrum. This objective required the team to determine how the spectrum is attenuated with aluminum, copper, and tin-based filters.

3.5.1 What Methodology will be Used

We compared previously conducted research with simulation results of absorbed doses recorded from MCNP5. Each model consisted of a tissue approximation that consisted of a thin layer of A-150 plastic developed by Shonka surrounding a small volume of tissue-equivalent propane gas. These materials are considered to be tissue equivalent because their interactions with ionizing energy closely model that which is observed in tissue (Smathers et al., 1977; Chriotti et al., 2015). An interchangeable metal X-ray filter of varying composition (Al, Cu, etc.) was placed in between the tissue model and a photon source (either Cs-137 or 320 kVp X-ray). Lead shielding was placed around the source to prevent the tissue model from interacting with any radiation that had not been attenuated which could introduce error into our simulations. We then examined the performance of several common interchangeable metal filters such as aluminum, copper, and Tin, to compare their abilities to that of the Cs-137 standard as can be seen in Table 1. In order to have each of these specific materials within our simulation, it was necessary that we knew the exact composition of these materials. The data that was collected and used for the simulation of these materials can be found in Table 2.

Table 1: Filter composition used for MCNP5 simulations.

Filter Type	Atomic Filter Composition	Thickness (mm)
Aluminum Filter	Al	2
Copper Filter	Cu	0.3
Mixed Filter	Al, Cu, Sn	1.5 Al, 0.25 Cu, 0.75 Sn

Table 2: Material card information used for MCNP5 simulations.

	Elemental Composition	Atomic #	Mass fractions	Density of material g/cm^3
Aluminum	Al	13	1	2.6989
Copper	Cu	29	1	8.94
Tin	Sn	50	1	7.31
Lead	Pb	82	1	11.432
Water	O H	8 1	0.334 0.666	1
Air	C N O Ar	6 7 8 18	0.00012 0.75527 0.23178 0.01283	0.001205
TE propane Gas	H C N O	1 6 7 8	0.103 0.565 0.035 0.293	3.14*10^-5
Shonka A-150	H C N O F Ca	1 6 7 8 9 20	0.1015 0.7755 0.035 0.052 0.0174 0.01838	1.127

3.5.2 How Data will be Acquired and Analyzed

Our data were acquired through our preliminary interviews as well as online databases such as the WPI Gordon Library Database, JSTOR, PubMed, and NCBI. We also acquired data through our simulations with MCNP5. An MCNP primer (Shultis & Faw, 2011) was provided that gave basic information on the functionality and usage of the software. From this document we had the information we needed in order to set up a simulation and collect data. The data were then analyzed using Excel.

3.5.3 Comparing MCNP to Previously Published Results

This methodology allowed us to compare our computational findings to previous research. Once we determined that our findings matched those of previously published figures, we then concluded through analysis and direct comparison which filters have the best performance through a ranking system. This ranking system was based around the quality and comprehensiveness of the data obtained, in comparison to a “standard” Cs-137 irradiator.

3.6 Limitations

Although most of our data collection and surveys were conducted virtually, due to the COVID-19 pandemic all of our interviews had to be conducted online over Zoom. The team originally believed that the pandemic would make it impossible to be able to see either type of the irradiators we are studying in person, but through our interview process we were able to plan and attend a tour of Massachusetts General Hospital to see their irradiators.

3.7 Ethics

This project was reviewed and approved by the WPI Institutional Review Board (FWA #00015024 - HHS #00007374). The simulation process using radiation transport codes ensured that the X-ray source was safe to use and would not affect those in a nearby range of the source. We also protected the privacy and anonymity of all involved parties where applicable and consent was obtained for every interview and survey that we conduct (See Appendix B). Any interviewee who did not specifically indicate they were willing to be named in our report were anonymized.

4. Results

4.1 Introduction

The results we obtained during our projects can be sorted into two different categories of analysis. First is the social aspect, collected through interviews and surveys. The results from our interviews and surveys allowed the team to analyze the key concerns of researchers and medical professionals alike, and use them to make recommendations on how blood banks and research facilities could encourage more facilities to switch from Cs-137 to 320 kVp X-ray irradiators. MCNP5 simulations were analyzed to evaluate differences between Cs-137 and 320 kVp X-ray irradiators computationally. X-ray filters were added to our models to determine how they could be used with non-radioisotopic alternatives. The simulation findings aided the team's work by providing quantitative data to help support our findings.

4.2 Interviews

We interviewed ten (10) individuals who have worked with Cs-137 and/or X-ray irradiators. These interviews consisted of professionals with different positions in the health physics fields to obtain a broad range of opinions. Interviews included professors, radiation safety officers, directors of radiation safety and research, and employees in environmental health and safety at hospitals. Most of them work in hospitals and facilities located in Massachusetts including: Massachusetts General Hospital, Boston Children's Hospital, etc. The team was also successful in conducting an interview with New York professionals (at Mount Sinai Health Systems) and California (at UC Irvine Health).

As the goal of the interviews was to gain a stronger understanding of the social aspects surrounding the problem, our interview questions were more geared toward opinion and experience rather than technical understanding. Our questions allowed the interviewee to reflect on the aspects of each irradiation type, and most importantly what they felt could be improved in each system. After this clarification, the questions transitioned to focus on whether or not the interviewee felt X-ray irradiators were an adequate switch. Finally, we asked each interviewee to elaborate on any concerns they may have had regarding the switch (see Appendix A).

4.2.1 Successful Switch to Non-Radioisotopic Irradiators

In an interview with the team Jacob Kamen, Senior Director Chief Radiation & Laser Safety Officer at Mount Sinai Health Systems (Kamen, 2021), discussed his facility's success in transitioning from Cs-137 to X-ray irradiators. Due to the fact that the hospital operates in a heavily populated area, the success of the switch involved a lot of security reinforcements. Mount Sinai created a three (3) phase action plan in order to prepare and switch to X-ray irradiators. Phase 1 provided for the worst-case scenario in which the hospital prepared to respond to radiological incidents. The hospital purchased monitors and protection equipment to read radioactive levels, installed radioactive detectors as well as decontamination showers, and performed drills with the police and fire departments. Phase 2 reduced the risk by limiting access to the Cs-137 irradiators, hardened security, and performed FBI background checks to ensure safety until Phase 3 could begin. Finally, Phase 3 provided for the elimination of their Cs-137 irradiators and fully switched to 320 kVp X-rays. According to Kamen, professionals at Mount Sinai are satisfied with using their X-ray units for irradiation and Kamen himself has published multiple papers comparing the two types of irradiators and about the success that he has had with X-rays (Kamen, 2019).

Barbara Hamrick is a health physicist who oversees the irradiation at UC Irvine Health in California (Hamrick, 2021). While Hamrick was the only contact on the U.S. West Coast with whom we were able to connect, she provided helpful information about the differences in protocols regarding X-rays and Cesium in California. UC Irvine Health was able to replace their Cs-137 irradiators with X-ray irradiators in 2019 and this transition was very successful. UC Irvine Health performs routine maintenance on their X-ray irradiators and have had no issues with the machine’s functionality thus far. UC Irvine used federal programs to make the transition and dispose of the Cesium-137. Hamrick stated that everything went really smoothly with the transition, but they would not have made this switch without the federal program. A notable difference regarding the protocols in California regarding X-ray irradiators is that they require employees who utilize X-rays to go through training and pass two exams before they can use the X-ray irradiators.

4.2.2 Problems Arising while Switching to Non-Radioisotopic Irradiators

We also spoke with professionals at two hospitals currently in the process of switching over from Cs-137 to X-ray irradiators and they were able to provide insight into problems arising from the transition. Interviewee A spoke with us about their facility's transition from Cs-137 irradiators to 320 X-ray irradiators (Interviewee A, 2021). Currently, their blood bank uses X-ray irradiators exclusively, and they have been pleasantly surprised about how easy it is to work these irradiators as compared to Cs-137 irradiators. Our interviewee noted that they would recommend it for blood products, but is still unsure about using it for research. They are concerned about the amount of energy that X-ray irradiators use and about their accessibility during a power outage. They mentioned complaints from their colleagues elsewhere about X-ray tubes requiring maintenance and replacing, but the hospital our interviewee works at has yet to run into these specific problems.

In addition, we interviewed an employee in the radiation safety department at Massachusetts General Hospital. Nick Borges, the Assistant Director of Radiation Safety, was able to discuss his hospital's process while using the CIRP program through the government (Borges, 2021). Through this program they were able to get a new X-ray unit at 50% of the average retail cost, but unfortunately, they have been waiting for the program to remove their Cesium irradiator for over a year now. Borges does believe that X-ray irradiators can be a viable alternative to Cs-137 irradiators, but the technology still needs time to improve as his facility is facing problems with the new irradiators breaking down. On the Massachusetts General Hospital campus about ⅗ of their X-ray irradiators are currently inaccessible, which poses an ongoing inconvenience. Borges also expressed worry about animal testing protocols that use Cesium, as it may be difficult to adapt already existing protocols to X-ray irradiation.

Interviewee B spoke with us about their concerns while transitioning from Cs-137 to 320 kVp X-ray irradiators (Interviewee B, 2021). They expressed understanding about the push to switch to non-radioisotopic irradiators, noting that a broken Cs-137 irradiator is much worse than a broken X-ray irradiator. A broken irradiator in general is very inconvenient and can put a hold on research and blood irradiators, but a broken Cs-137 irradiator requires evacuation of the area as the powder form of Cesium could be released into the air. While they have found that X-rays provide better dosimetry, unfortunately, the hospital's X-ray irradiators have not functioned as well as hoped as they have been requiring more maintenance than their Cs-137 irradiators do, and these X-ray irradiators are only five and seven years old. Our interviewee also mentioned that the installation of an X-ray unit may require building modifications, taking the process longer to complete.

4.2.3 Concerns with Non-Radioisotopic Irradiators

The biggest concern among those we've interviewed is the amount of time the switch would take. Currently, it takes roughly 12-18 months to install a new X-ray unit and even longer to properly get rid of the Cesium unit. In addition to time, another major concern centers around the irradiator protocols. X-ray units are not included in current irradiation protocols, implying that if the switch were to be made, those protocols would have to be re-written. These concerns were mentioned by multiple interviewees and, as explained below, were frequently mentioned in our survey responses.

Boston Children's Hospital's Director of Research Lab Support, William Lorenzen, was able to provide us with a different opinion on X-ray irradiators than we had received in our previous interviews (Lorenzen, 2021). Lorenzen works with Cs-137 irradiators and hasn't personally used X-rays before as they do not have one in his facility, but he does know about them and is concerned about how quickly the government is trying to replace the Cesium irradiators by supporting X-ray units. He stated that X-rays have only been on the market for a short period of time and that there are very limited vendors. Thus, he is concerned about their reliability by comparison with that of Cs-137 irradiators, which he considers very reliable and less in need of maintenance. Lorenzen was also the only interviewee who discussed other alternatives that could be used for irradiation such as pathogen inactivation.

4.3 Survey Results

Based on the responses the team acquired through our interviews with health physics professionals, we were able to generate a survey that would allow members of the community to air their concerns regarding the switch while simultaneously collecting quantifiable data on subjects like the type of irradiators being used. The team asked those previously interviewed and our sponsor, Matthew Carey, to distribute the survey and we were able to receive thirty-five

(35) responses from irradiation users including blood bank workers, radiation safety officers, and researchers. The survey inquired about the types of irradiation that the user performs (such as blood or cells) and what type of irradiators they have used (X-ray or Cesium-137.) These questions helped the team organize the responses based on user occupation, as well as type of irradiation utilized. Additionally, the survey asked how willing the participant was to use X-rays as their sole source of irradiation based on a 10 point scale with 1 being unwilling and 10 being completely willing. The survey also allowed them to list any concerns about switching from Cs-137 to 320 kVp X-rays.

4.3.1 Population Descriptions

Two (2) questions of our survey inquired about the position that the individual has that allows them to work with irradiators, as well as what use that they have for them. The population studied through the survey, which can be seen in Figure 11, consisted of seven (7) radiation safety officers, two (2) blood bank workers, one (1) health physicist, and twenty-six (26) researchers from varying institutions and workplaces.

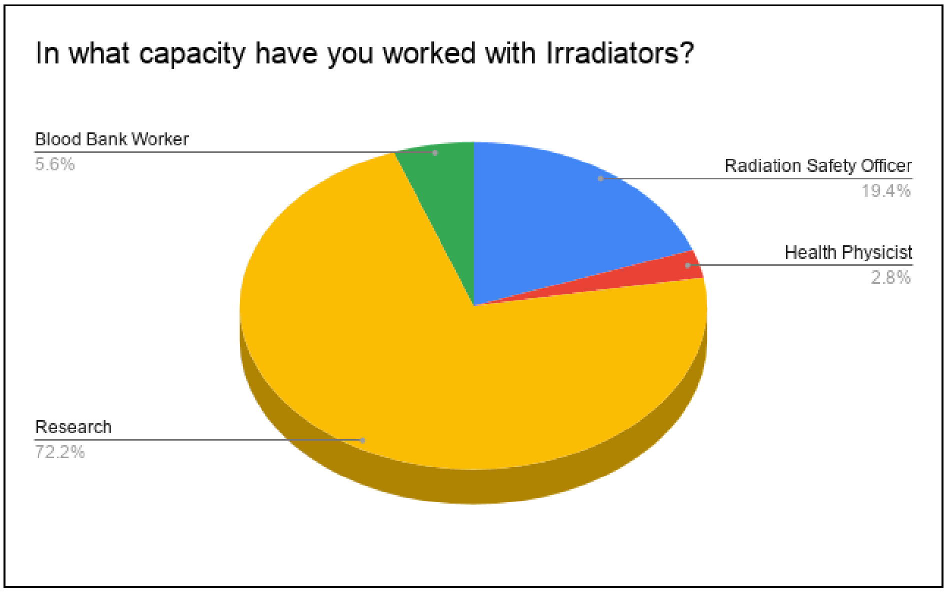

Figure 11: Survey population occupations.

Among this group, irradiation was used primarily for cells, blood irradiation, and whole animal irradiation including that of mice, rats, and zebrafish. Responses were formatted to fit into the following categories: Cells, Animals, Blood, and Miscellaneous, where miscellaneous consisted of practices such as sterilization of food or masks. Many researchers selected multiple uses when filling out this portion of the survey and their responses can be seen in Figure 12 below.

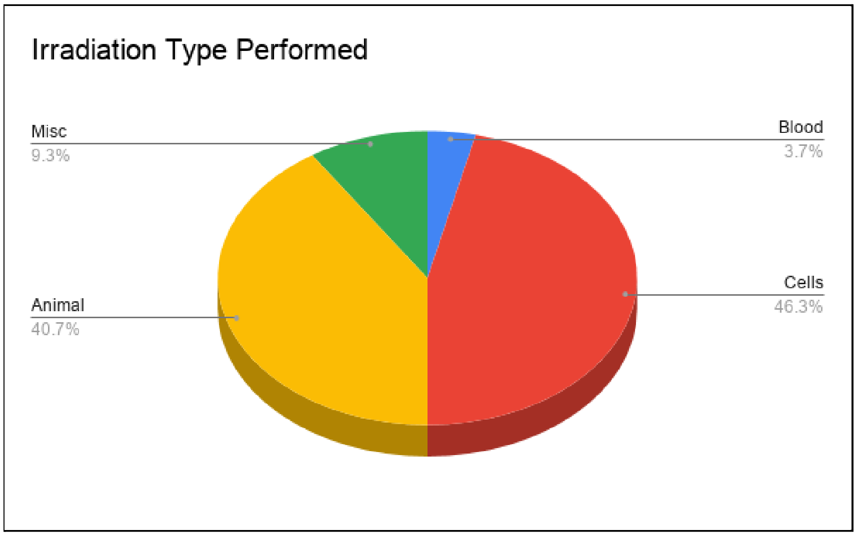

Figure 12: Type of irradiation performed by survey participants.

The participants were then asked if they have ever used Cs-137 and 320 kVp X-ray irradiators. This question helped the team understand the work performed and concerns of our participants based on which type of irradiators they have used. It was determined that the majority of participants taking our survey, 91.4%, have previously used Cs-137 irradiators. This high number was expected since Cs-137 is the most common source of irradiation. In terms of X-rays, only 54.3% of participants had used X-rays before.

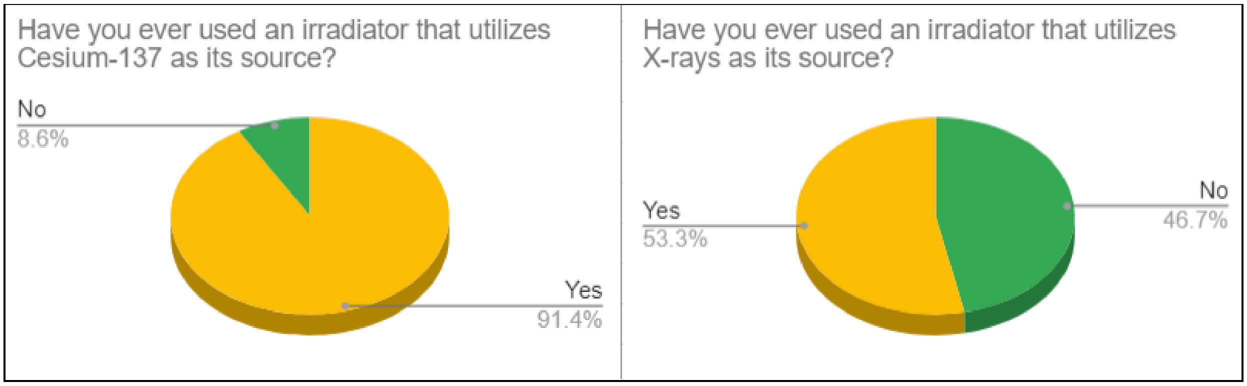

Figure 13: How many of our participants have used Cs-137 & X-ray irradiators.

4.3.2 Willingness to solely use X-rays

The survey asked participants how willing they were to use X-rays as their sole source of irradiation on a scale of 1 to 10. While we did receive a wide range of answers with multiple responses on both sides of the scale, ten (10) of our thirty-five (35) participants (28.6% of answers received) were fully willing to use X-rays as their sole source of irradiation, rating their willingness at ten (10). The majority of participants were at least somewhat willing (responses with a "5" or above) to make the switch.

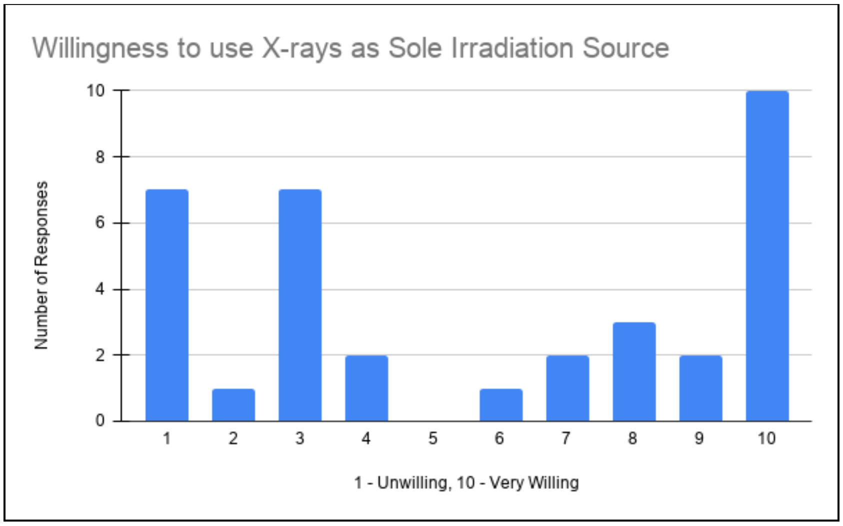

Figure 14: Participant's willingness to use X-rays as their sole source of irradiation.

As visible in Figure 14, 48.6% of responses were on the lower end of the rating scale (below a rating of "5"). Ratings of 1 (unwilling) and 3 on the scale each received seven (7) responses which accounted for 40% of our survey participants. While this may seem to indicate sizable opposition to X-ray irradiators, it's worth noting that a majority of these responses were from participants who have never used X-rays before. Out of the seventeen (17) participants who rated their willingness to use X-ray irradiators below 5, eleven (11) had never used X-rays before. It is possible that they are unaware of the resources available to aid with the switch from Cs-137 to X-rays, or have yet to learn about the success of X-rays at other facilities.

4.3.3 Major Concerns

Based on our previous research from our literature review the team created a list of common concerns that health physics professionals may have about X-rays and invited our survey participants to indicate which, if any, they shared. These concerns included: dose uniformity across a sample, accuracy, obstruction of current research projects (such as switching irradiator types mid-research which could invalidate already collected data), cost, maintenance, and inconvenience, particularly given the potentially long installation process. The team also provided a section for participants to write in additional other concerns. The main goal of this question was to understand major concerns that the team should focus on in making recommendations for encouraging the switch to 320 kVp X-ray irradiators. As seen in Figure 15 the two largest concerns recorded were inconsistency with or obstruction of current research projects and dose uniformity across a sample.

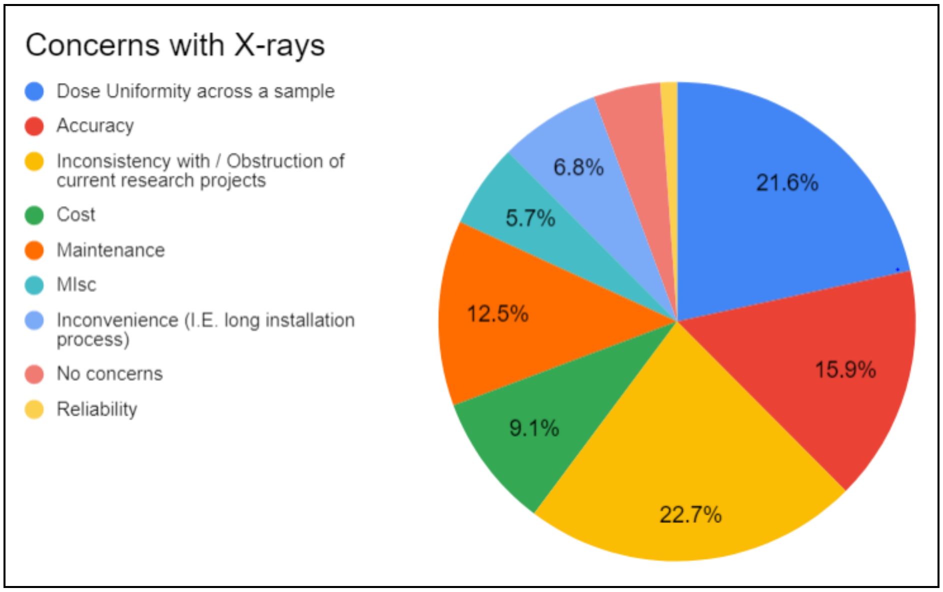

Figure 15: The concerns that our survey participants have when switching from Cs-137 to X-ray irradiators.

The final question of our survey asked if there was anything else participants would like to mention regarding the topic. This open response section provided key insight, with about a third of our participants sharing more personal thoughts on the topic. About half of those who responded mentioned that they have been satisfied with their facility's switch from Cs-137 to X-rays. Other answers involved concerns with maintenance, long installation times, long training times, and expenses.

4.3.4 Other Survey Received

As mentioned earlier, we were able to compare our survey data with those from a similar study. This survey received responses from researchers and posed very similar questions to those that we asked. As seen in Figure 16, only 36.8% of those surveyed said that they wouldn't want to transition, while 33.0% saying they would, 25.5% were unsure and 1.9% were already using X-ray irradiators.

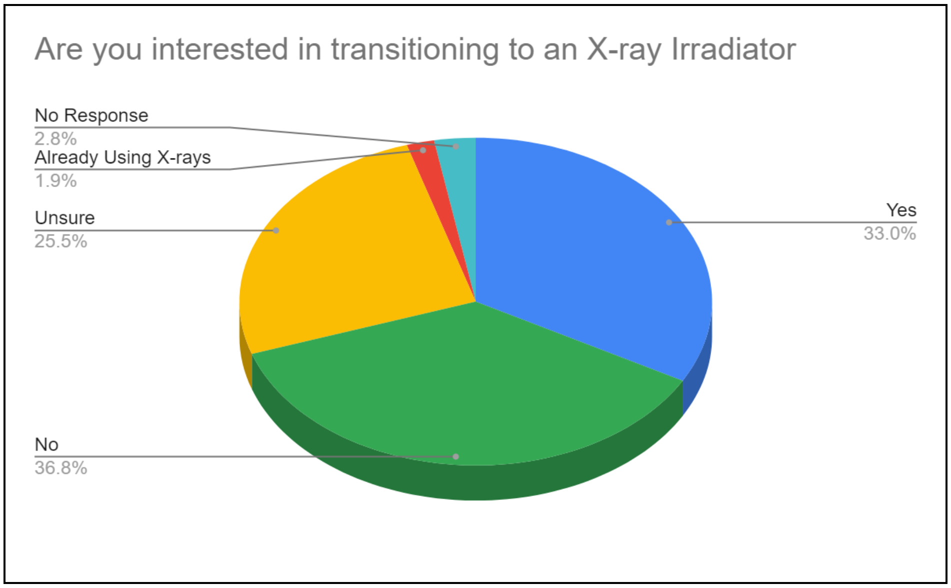

Figure 16: Responses regarding interest in transitioning to X-ray irradiator ("National Institutes of Health (NIT) survey results about Cs-137 & X-ray irradiators", 2021).

The survey also enabled participants to list their concerns regarding the transition to 320 kVp X-rays. A frequent concern that the participants shared was the obstruction of current research projects that use Cs-137 irradiators. This concern was brought up for two main reasons. One was due to participants working on studies with Cs-137 that have been going on for multiple years and they do not wish to change the way they have been conducting their research. The other reason this concern was frequently brought up was due to participants not believing that X-ray irradiators would provide the same results of a Cs-137 irradiator. Multiple participants indicated that they did not want to go through the process of replacing their irradiators, or that they know that Cesium works well and they do not want to fix an already working system. Other concerns included X-ray units breaking down, having to have a designated space for an X-ray irradiator, the need for professional staff and training to operate the X-ray units, the procedure for disposing of their Cesium, and the lack of information about the differences between the two types of irradiators ("National Institutes of Health (NIT) survey results about Cs-137 & X-ray irradiators", 2021).

4.4 MCNP5 Comparison of Cs-137 & X-ray Irradiators

In order to compare the Cs-137 and X-ray irradiators, we used MCNP5 to generate a model environment to determine the doses delivered to a model tissue from both sources. In order to test this, a simple model was created consisting of a lead shielding surrounding a source with an open end to direct the emitted photons. These emitted photons would collide with the thin TE plastic surrounding our model and create an emitted electron within the gaseous interior. The energy of this electron was recorded in order to determine the amount of energy the electron deposited per micron within the model (Kev/um). MCNP5 reports the data in terms of a tally, this tally reports how many times that lineal energy was detected over the course of the simulation. The reported data can be seen in Figure 17, while this graph is able to tell us a lot about the strength of the signal as reported by the software it makes it difficult to numerically compare the peaks of these types of irradiation. In order to better understand our data, we created another graph seen in Figure 18 that shows the two peaks scaled to the same values for easy comparison.

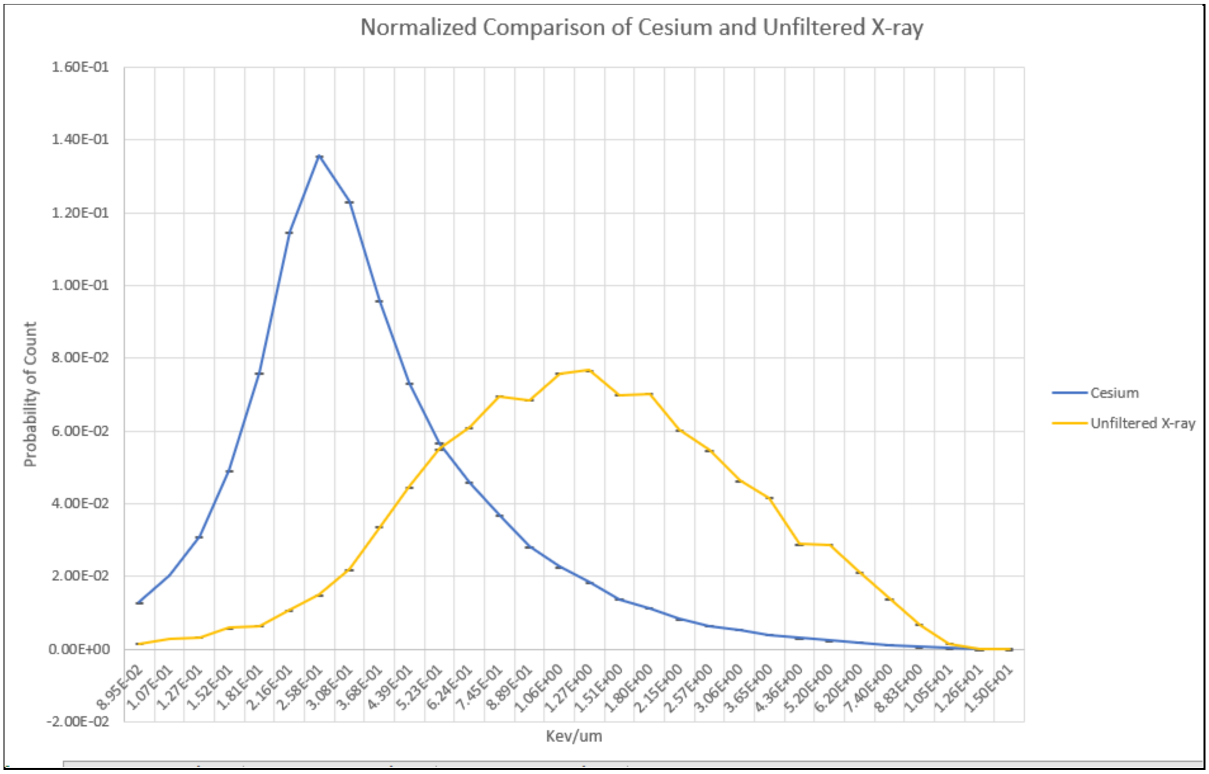

Figure 17: Normalized comparison of Cesium and unfiltered X-ray.

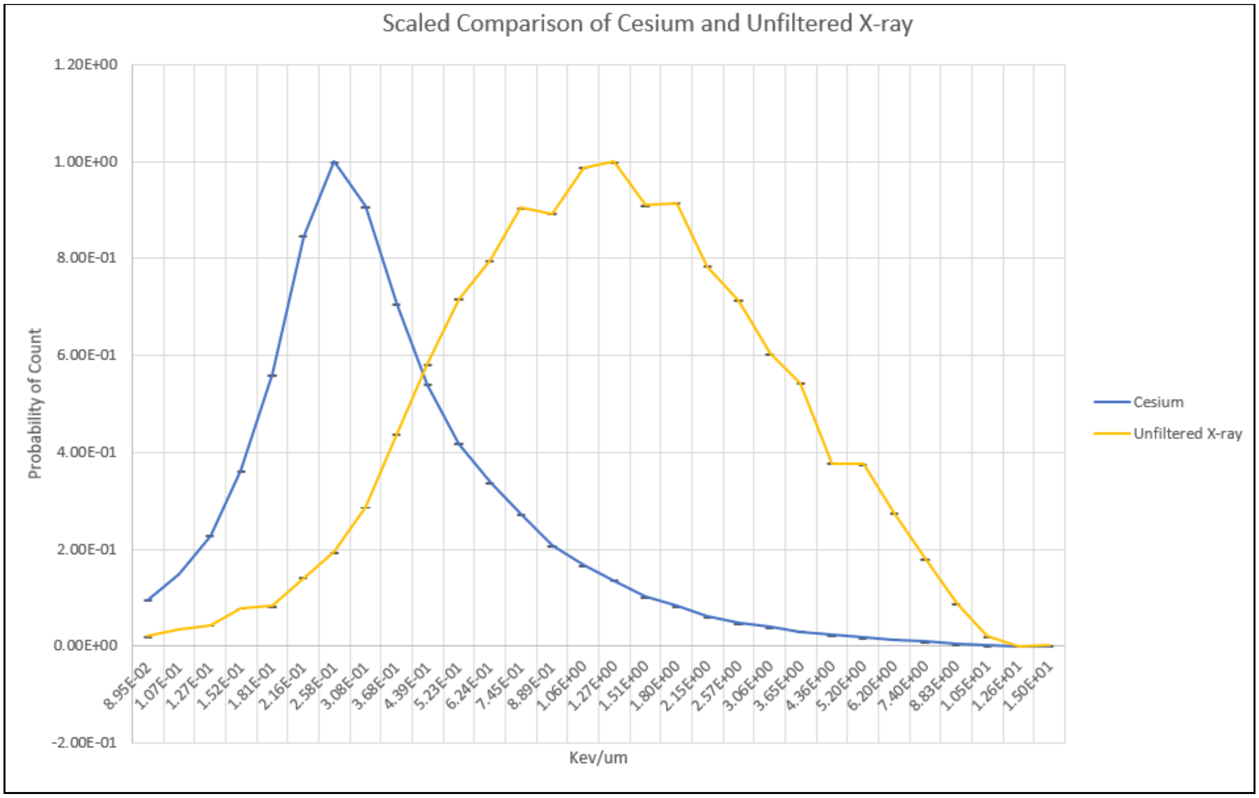

Figure 18: Scaled comparison of Cesium and unfiltered X-ray.

As can be seen above the LET of X-ray is actually higher than that of Cs-137. This is likely due to the fact that the X-ray photons start out as lower energy allowing more photoelectric events to occur. The photoelectric effect allows an incident photon to transfer its energy better to an emitted electron when compared to Compton scattering which also emits a low energy photon, taking energy away from the emitted electron. Due to this fact, X-ray is more than capable of delivering the energy required to break the DNA and kill a T cell within an irradiator.

4.5 MCNP5 X-ray Filter Analysis

In order to compare the attenuating effects of different X-ray filters, three different geometries were constructed in order to analyze the difference in microdosimetry. The first of these scenarios consists of an X-ray source passing through a filter made of 2 millimeters of aluminum. The second scenario is similar to the first, consisting of 0.3 millimeters of copper. The final filter is a layered material consisting of 1.5 mm of aluminum, 0.25 mm of copper, and finally a 0.75mm layer of tin. These three filters were placed 10 centimeters away from the TE gas-filled plastic sphere. We placed the filters close to the source and overtop of the lead shielding in order to ensure that there were no X-rays hitting the phantom that had not been attenuated by the filter. In order to begin investigating this objective, we wanted to determine how much an X-ray filter will adjust the LET spectrum from an unfiltered X-ray as can be seen in Figure 19.

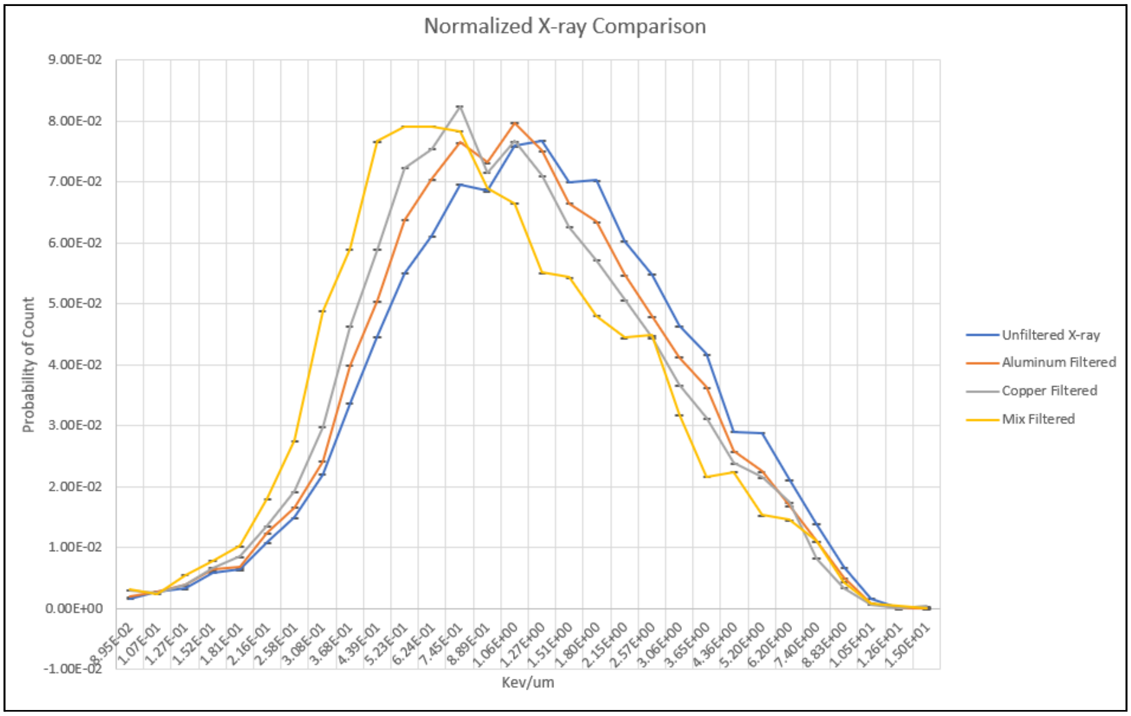

Figure 19: Normalized comparison of X-rays.

The filters were capable of decreasing the recorded LET produced by the X-rays. The Aluminum filter provided the least amount of attenuation, likely due to the fact it was the least dense and had the lowest atomic number of all of the filters tested. Next was the copper filter which was able to attenuate more than the aluminum filter despite being nearly ten times thinner than the aluminum filter likely due to its higher density and atomic number. Finally, the mixed filter was able to provide the most attenuation seeing as it combines the properties of both aluminum and copper while also adding an even heavier element, tin. The next step was the comparison of the filtered X-rays to the LET spectrum of Cesium. Below, in Figure 20, the normalized comparison of X-rays and Cesium is shown. The magnitude of the Cesium peak makes comparison difficult so the scaled graph can be seen in Figure 21.

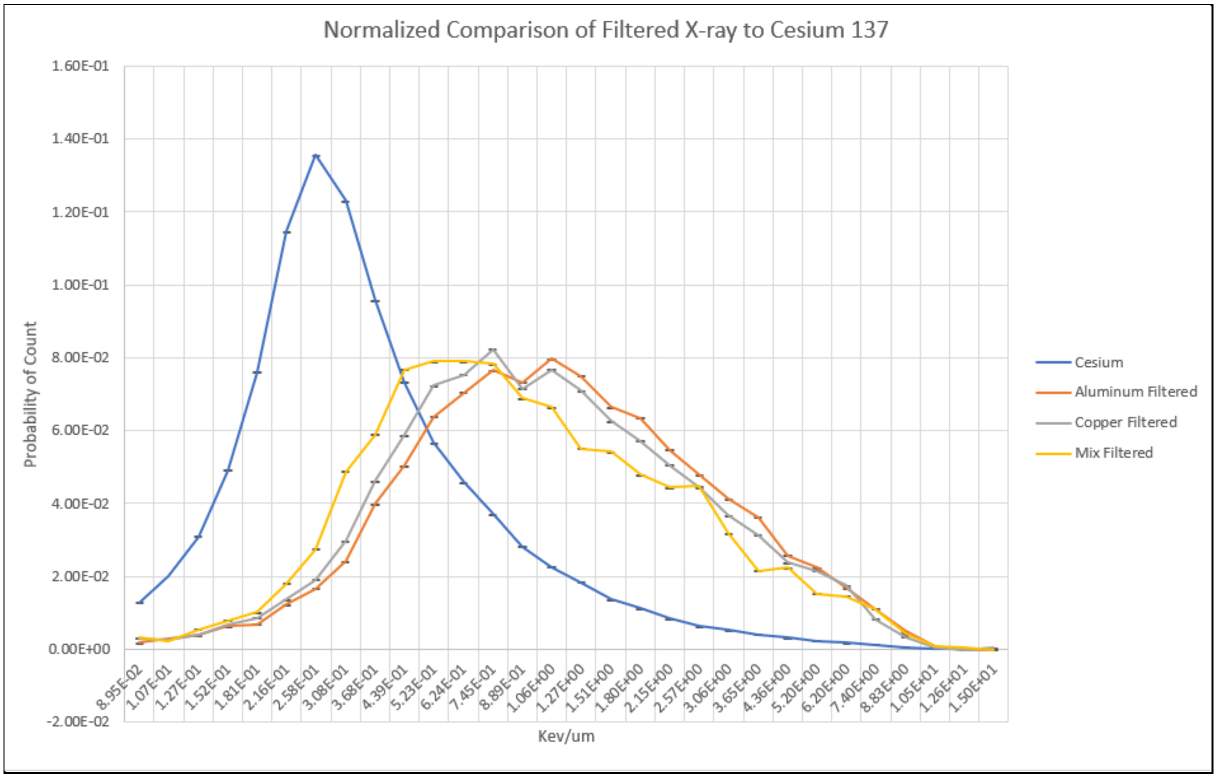

Figure 20: Normalized comparison of filtered X-ray and Cs-137.

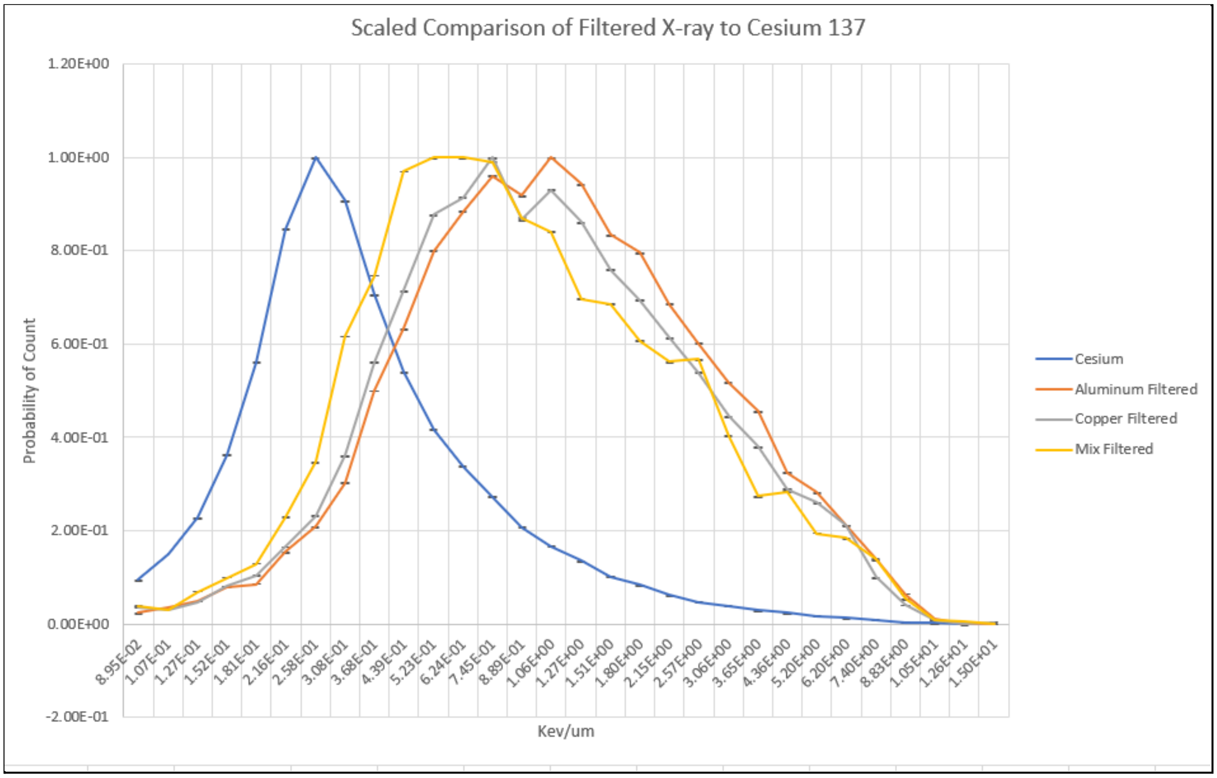

Figure 21: Scaled comparison of filtered X-ray and Cs-137.

In order to better directly compare the difference between each type of filtered radiation relative to Cesium, we have recorded the highest peak of each spectrum in Table 3. As can be seen, Cesium has the lowest LET out of any of the test groups. The mixed filter design allows the X-rays to more closely match that of Cesium but it still isn't a perfect match to the Cesium spectrum.

Table 3: Strongest recorded LET for each type of radiation.

Filter	Composition	Thickness (mm)	Peak Kev/um
Filter 1	Al	2	1.06
Filter 2	Cu	0.3	0.745
Filter 3	Al, Cu, Sn	1.5, 0.25, 0.75	0.624
Cesium	N/A	N/A	0.258
Unfiltered X-ray	N/A	N/A	1.27

5. Discussion and Recommendations

5.1 Introduction

Throughout the course of this project, the team was able to collect both qualitative and quantitative data to aid in the evaluation of the viability of X-ray irradiators as alternatives to Cs-137. The social data we were able to collect consisted of statements from the ten (10) interviews that we conducted, and thirty-five (35) responses from the survey we created, as well as a comparison of these results with those from a previously conducted survey that was given to us through networking. We also collected quantitative data through simulations conducted via MCNP5, which allowed us to directly compare the linear energy transfer spectrum of both Cs-137 and X-ray irradiators.

5.2 Key Findings for encouraging the transition to X-ray irradiators

Our interviews and survey data indicate that there are multiple hospitals and research facilities that have either successfully fully transitioned to X-ray irradiators, are currently in the process of making the transition, or are willing to make the change. While many still oppose this change, we believe that many of these concerns can be addressed and dispersed through means of identifying misconceptions and informing the public about options for facilitating this transition and the alternative technologies' capability to irradiate.

5.2.1 Addressing concerns from our participants

From the survey that we administered, we learned that 9.1% of our participants were concerned with the cost of the transition as well as an additional comment on our survey regarding it (and multiple comments concerning cost on the additional survey we received). Through the Office of Radiation Safety (ORS) and the Cesium Irradiator Replacement Program (CIRP) the cost of disposing of any Cesium irradiator can be covered as well as up to 50% of the cost for a new X-ray irradiator (Office of Radiological Security, 2018). These types of programs are a valuable resource in that they make the transition process significantly easier and less costly on the consumer, and should be recommended to any facility with a Cs-137 irradiator. Another concern brought up in both our survey and the survey provided to us was intensive training processes. X-ray irradiators are actually easier to train on and don't require the lengthy background check that Cs-137 irradiators have. This transition should make it easier for hospitals and research facilities to train new employers and will grant easier access to these machines.

5.2.2 Successful transition is possible

Through this study, we have found several resources that can help with the transition to 320 kVp X-rays and we have talked with two facilities that used these resources to fully switch over from Cs-137 irradiators. Both these facilities have had successful transitions and are receiving adequate results with their X-ray irradiators for both blood bank irradiation and research. Hospitals such as Massachusetts General Hospital, which have successfully begun switching to X-ray irradiation, provide a template and example for all other facilities looking to do the same, and hint at the potential of their success. Five comments were left on our survey supporting the transition and discussing their experience (see Appendix D). In these comments, the participants discussed how they have had successful transitions to 320 kVp X-ray irradiators and many of them said that they had no problems so far with their new irradiators. From the survey provided to us there were multiple responses of people eager to make the change to 320 kVp X-ray irradiators and multiple others that wanted to participate in a comparison study. As time goes on, more and more facilities are replacing their Cs-137 irradiators with X-ray irradiators and are being satisfied with this transition.

5.2.3 MCNP5 comparison

The results of our MCNP show that both Cesium and 320 Kvp X-ray are more than capable of delivering the energy required to destroy a T cell and its DNA. Especially considering that the time spent in the irradiator can be increased or decreased to deliver more energy to the cells. The X-rays were able to deliver more energy per micron within the tissue model than the Cesium which may imply that X-rays are better at delivering energy deeper into the sample. It has been shown that radiation with higher LET's are more effective at killing cells because the cells have less ability to repair strand breaks after being hit with higher LET radiation (Ritter & Tobias, 1977). Due to this fact, it may prove that X-rays are better at creating non-repairable breaks within a cell, although further investigation of this is necessary.

5.2.4 MCNP5 filters

Based on our research, we found the most common filter materials to be brass, copper, aluminum, lead, tin, titanium, tungsten, molybdenum, and zirconium. However, for our MCNP5 simulations, we focused on the materials aluminum, copper, and tin. Our first filter is a 2mm layer of Aluminum. Secondly, we tested a filter that was a combination of a 1.5mm layer of Aluminum, a 0.25mm layer of Copper, and a 0.75mm layer of Tin. Lastly, our third filter is a 0.3mm layer of Copper. In the end, our mixed filter design provided the best approximation of the Cs-137 LET spectrum relative to the other models that were tested. In the future, testing with even more filter types and thickness may be able to provide an even more accurate approximation of the Cesium linear energy transfer.

5.3 Recommendations

It is very important to inform consumers about the potential risks and benefits before switching to X-ray irradiators and the team believes that with the right resources, such as that of the government-funded programs discussed previously, all facilities should be able to make the transition within the next decade or sooner. If health physics professionals and their institutions take advantage of these programs, this process should not be expensive, will make access to irradiators easier for researchers and employees, and will overall make the U.S. safer. Based on our findings, the team recommends that all hospitals and research facilities work with government-funded programs (i.e., CIRP) to dispose of their Cs-137 irradiators and obtain partial funding for new X-ray irradiators. This would save facilities hundreds of thousands of dollars in disposal costs for their Cs-137 irradiators, and enable them to obtain a new irradiator at half the cost. Considering that, given Cesium's half-life of 30 years, these facilities would otherwise have to dispose of their old Cesium sources eventually, government assistance with disposal could save them a lot of money.

Multiple research facilities and simulation programs have proved that X-ray irradiators can fulfill the same needs as do Cs-137 irradiators and have succeeded in doing so. But it's understandable that many people may have doubts about changing irradiators for specific projects. These doubts often stem from the fact that research may not have been published for the specific cell or animal irradiation type that a researcher performs. The team also understands this transition could interrupt current research projects with Cs-137 written into the protocols. We still recommend that hospitals and research facilities explore how government programs may help them dispose of their Cs-137 irradiators. Our simulation data shows that with a filter consisting of aluminum, tin, and copper, the LET spectrums of Cs-137 and X-ray irradiators are similar, but we do believe that additional studies be conducted into the thickness and composition of filters in order to make the LET of X-ray close to that of Cesium in hopes that it may be able to provide an acceptable replacement for researchers with already published papers.

We also recommend that government programs like the ORS work to ensure that replacement parts are available for X-ray irradiators given that these can require more maintenance than Cs-137 irradiators. With the population we studied, there were several facilities that noted that they needed to perform a lot of maintenance on their X-ray irradiators and had to buy multiple replacement parts to fix their X-ray irradiators. On the other hand, there were also many facilities that have had their X-ray irradiators for years with no or minimal trouble in terms of maintenance. While the possibility of additional maintenance may seem burdensome, a broken X-ray irradiator is much safer and much easier to fix than a broken Cs-137 irradiator. We have found that the facilities that perform routine preliminary maintenance on X-ray irradiators experience little to no breakdowns, and we recommend this practice to all facilities that are fully transitioning from Cs-137 to X-ray irradiators.

The replacement of Cs-137 irradiators with 320 kVp X-ray irradiators will not occur overnight, and while we do recommend that hospitals and facilities make this transition, it is understandable that it could disrupt important research. If facilities are unable, or unwilling, to discontinue the use of Cs-137 irradiators, we suggest that they nonetheless make a plan to transition to X-ray irradiators within the next decade. Having a transition plan will make it much easier to carry out the transition when the time does come, and it would hopefully give these research facilities enough time to finish their Cs-137 studies. There is a current objective set by the John S. McCain National Defense Authorization Act to eliminate Cs-137 irradiators in the U.S. by 2027. Though it is still only an objective, yet to be achieved, our team believes that it is pertinent for researchers to switch to X-ray irradiation immediately or as soon as possible, as the transition process may take longer than intended, and could have unforeseen consequences if not planned in advance. Switching to X-ray irradiators will provide researchers with the benefit of lessened security, radiological risk, background checks, and training, all while preserving the integrity of accurate irradiation. We hope that our findings will enlighten researchers of the immediate benefits of this switch, and allow them to consider making the switch in a timely manner.

Bibliography

Abdulla, S. (n.d.). Production of X-rays. Retrieved August 29, 2020, from https://www.radiologycafe.com/radiology-trainees/frcr-physics-notes/production-of-X-ray

Andersen AHF, Nielsen SSF, Olesen R, Harslund JLF, Søgaard OS, et al. (2020) Comparable human reconstitution following Cesium-137 versus X-ray irradiation preconditioning in immunodeficient NOG mice. PLOS ONE 15(10): e0241375. https://doi.org/10.1371/journal.pone.0241375

Andreo, P. (2018). Monte Carlo simulations in radiotherapy dosimetry. *Radiation Oncology, 13*(121). doi:https://doi.org/10.1186/s13014-018-1065-3

Backgrounder on Dirty Bombs. (2018, May). Retrieved from https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-dirty-bombs.html

Borges, N. (2021, April 1). Nicholas Borges Interview [Online interview].

Chiriotti, S., Moro, D., Colautti, P., Conte, V., & Grosswendt, B. (2015). Equivalence of pure propane and propane TE gases for microdosimetric measurements. Radiation protection dosimetry, 166(1-4), 242–246. https://doi.org/10.1093/rpd/ncv293

Choppin, G. R., & Rydberg, J. (2002). Absorption of nuclear radiation. *Radiochemistry and Nuclear Chemistry, 3*, 123-165. Retrieved from https://www.sciencedirect.com/topics/chemistry/compton-effect.

Effects of ionizing radiation on blood and blood components: A survey. (1997). *International Atomic Energy Agency: Industrial Applications and Chemistry Section*. Retrieved from https://www-pub.iaea.org/MTCD/publications/PDF/te_934_prn.pdf.

Farkas, J., & Mohácsi-Farkas, C. (2011). History and future of food irradiation. Trends in Food

Science & Technology, 22(2-3), 121-126.

Gott, K. M., Potter, C. A., Doyle-Eisele, M., Lin, Y., Wilder, J., & Scott, B. R. (2020). A comparison of Cs-137 γ Rays and 320-kV X-rays in a mouse bone marrow transplantation model. Dose-response : a publication of International Hormesis Society, 18(2), 1559325820916572. https://doi.org/10.1177/1559325820916572

Goudarzi, Maryam, et al. "Development of urinary biomarkers for internal exposure by Cesium-137 using a metabolomics approach in mice." *Radiation Research*, vol. 181, no. 1, 2014, pp. 54–64., www.jstor.org/stable/24545102. Accessed 9 Feb. 2021.

Hamrick, B. (2021, April 23). Barbara Hamrick Interview [Online interview]

Hanania, J. Stenhouse, K. Donev, J. (2017) Gamma decay. *Energy Education.* Retrieved from: https://energyeducation.ca/encyclopedia/Gamma_decay#cite_note-2

Interviewee A (2021, March 30). Anonymous Interviewee A Interview [Online interview]

Interviewee B (2021, April 9). Anonymous Interviewee B Interview [Online interview]

Kamen, J., Hsu, W., Boswell, B. Hill. (2019) Successful migration from radioactive irradiators to X-ray irradiators in one of the largest medical centers in the US. *Health Physics.* 117:5, 558-570 doi: 10.1097/HP.0000000000001095

Kamen, J. (2021, April 7). Jacob Kamen Interview [Online interview]

Klassen, S. (2011). The photoelectric effect: Reconstructing the story for the physics classroom. *Science & Education, 20*, 719-731. Retrieved from https://link.springer.com/article/10.1007/s11191-009-9214-6.

Kramer, D. (2017, October 24). Push to purge cesium irradiators gains momentum. Retrieved from https://physicstoday.scitation.org/do/10.1063/pt.6.2.20171024a/full/

Lorenzen, W. (2021, April 12). William Lorenzen Interview [Online interview]

Moroff, G., & Luban, N. L. C. (1997). The irradiation of blood and blood components to prevent graft-versus-host disease: technical issues and guidelines. Transfusion Medicine Reviews, 11(1), 15-26.

Murphy, A., & Goel, A. (n.d.). Filters. Retrieved March 16, 2021, from https://radiopaedia.org/articles/filters?lang=us

Murphy, A., & Goel, A. (2020). Kilovoltage peak. Retrieved from https://radiopaedia.org/articles/kilovoltage-peak?lang=us#:~:text=Kilovoltage%20peak%20(kVp)%20is%20the,quality%20of%20the%20photons%20generated.

[National Institutes of Health (NIT) survey results about Cs-137 & X-ray irradiators]. (2021). Unpublished raw data.

Replacing Cesium-137 irradiators: Leaders taking steps. (2018, November 20). Retrieved from https://www.nti.org/analysis/articles/leaders-field/

Ritter, m., Cleaver, J. & Tobias, C. High-LET radiations induce a large proportion of non-rejoining DNA breaks. Nature 266, 653–655 (1977). https://doi.org/10.1038/266653a0

Saglam, S. (2011). Blood irradiation. in modern approaches to quality control. IntechOpen.

Shultis, Kenneth J, and Richard E Faw. “An MCNP primer.” Kansas State University, 12 Dec. 2011.

Smathers, J. B., Otte, V. A., Smith, A. R., Almond, P. R., Attix, F. H., Spokas, J. J., Quam, W. M., & Goodman, L. J. (1977). Composition of A-150 tissue-equivalent plastic. Medical physics, 4(1), 74–77. https://doi.org/10.1118/1.594380

Stacey, G., & Vestrand, T. (2001). Gamma-ray astronomy. *Encyclopedia of Physical Science and Technology, 3*, 397-432. Retrieved from https://www.sciencedirect.com/topics/earth-and-planetary-sciences/bremsstrahlung.

Transitioning from high-activity radioactive sources to non-radioisotopic (Alternative) Technologies , The White House , 2016, pp. 1–48.

Zubair, Abba C. “Cesium-137 chloride blood irradiators.” Received by Cynthia G. Jones Ph.D, 26 Sept. 2008, Washington, D.C.

Appendix A: Interview Protocol & Questions

The goal of our interviews is to ask open-ended questions that will help shape the questions on our surveys.

Introductions:

Overview of introduction

- Brief introductions of who we are, mention our relation to the person who gave us their contact (i.e. our advisors or Dr. Carey)
- Consent to record the interview
- Overview of our project and why we are interviewing them
- Give the interviewee an opportunity to answer any clarifying questions before we begin the interview.

Questions

Questions:

Profession	Question
Doctors	Have you ever used cesium-137 irradiators or X-ray irradiators?
	What is your use for irradiators?
	What do you know about 320 kVp X-ray irradiators and their efficiency?
	Based on what you know about kVp X-rays, do you feel as though they are an adequate alternative to Cs-137 Irradiators? Why or why not?
	More specifically what are your biggest concerns when considering the switch to X-ray irradiators?
Researchers	Have you ever used cesium-137 irradiators or X-ray irradiators?
	What is your use for irradiators for the research you are working on?
	What do you know about 320 kVp X-ray irradiators and their efficiency?
	Do you believe you would be able to continue your research by solely using X-ray irradiators? Please explain

	What are your biggest concerns when considering the switch to X-ray irradiators?
Blood Bank Employee	Have you ever used cesium-137 irradiators or X-ray irradiators?
	What do you know about 320 kVp X-ray irradiators and their efficiency?
	Do you believe you would be able to continue your work by solely using X-ray irradiators? Please explain
	More specifically what are your biggest concerns when considering the switch to X-ray irradiators?
Others knowledgeable on the subject	Have you ever used cesium-137 irradiators or X-ray irradiators?
	What do you know about 320 kVp X-ray irradiators and their efficiency?
	Based on what you know about kVp X-rays, do you feel as though they are an adequate alternative to Cs-137 Irradiators? Why or why not?
	More specifically what are your biggest concerns when considering the switch to X-ray irradiators?

Question Guidelines for all:

- All questions should be in an open-ended format.
- Do not include multiple questions in the same question, ask a follow-up question instead.
- Avoid using terms that may be familiar to us but unfamiliar to the interviewee.
- Pay attention to the order in which questions are asked.

Follow-up questions:

Questions that are not initially listed but are necessary to clarify details or to further investigate points the interviewee makes.

- Is there any piece of information we haven’t touched on that you wish to discuss further?

Going Further:

Resources to look into that we may not be already aware of, Colleagues or professionals who we may be able to interview as well.

- Would you be willing to complete a survey if we provided one to you in the future?
- Do you have any colleagues that would be willing to complete a survey about blood irradiators?
- Are there resources on this topic you find helpful that we may not be already aware of?
- Are there any questions you may have for us?

Appendix B: Interview Consent Form Agreement

Informed Consent Agreement for Participation in a Research Study

Investigator:

Contact Information: The investigators can be reached by emailing [redacted]

Title of Research Study: Comparing the Linear Transfer Distributions of Cs-137 and X-ray Irradiators for Use Within Hospitals and Research Facilities

Sponsor: Matthew Carey

Introduction
You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study: To compare the linear transfer distributions of Cs-137 and 320 kVp X-Ray irradiators for use within hospitals and research facilities.

Procedures to be followed: The following interview will take between 20 to 60 minutes to complete. During this time you will be asked a series of questions regarding both Cesium-137 and X-ray irradiators.

Risks to study participants: There are no foreseeable risks associated with this study.

Benefits to research participants and others: We are unable to provide benefits for participation in this study.

Record keeping and confidentiality: We would like your permission to record this interview for record keeping purposes. These recordings will be kept confidential among the investigators in order to maintain privacy. If we would like to directly quote you, we will arrange another meeting or email correspondence in order to ensure that the appropriate context is kept. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee, and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of injury: While an injury as a result of this study is unlikely, it is important to note that you do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

IRB Chair - Professor Kent Rissmiller, Tel. 508- 831-5019, Email: kjr@wpi.edu

Human Protection Administrator - Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu.

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Study Participant Signature: ________________ Date: ___________________

____

Study Participant Name (Please print)

Signature of Person who explained this study: Date:

Appendix C: Survey Questions

In what capacity have you worked with irradiators? Select all that apply. If 'other', please specify.

- Doctor
- Researcher
- Blood Bank Worker
- Other (Specify)

What process have you utilized irradiators for? (Select all that apply)

- Blood Irradiation
- Sterilization
- Other (Specify)

What level of accuracy do you require in your irradiations?

- <5%
- 5-20%
- 20-50%
- 50-75%
- >75%
- N/A

What types of irradiations do you perform?

- Cells
- Animals
- Other (Specify)

If animal, please specify cell type. If other, specify here.

- (Open Response)

Have you ever used an irradiator that utilizes Cesium-137 as its source?

- Yes
- No

Have you ever used an irradiator that utilizes X-rays as its source?

- Yes
- No

On a scale of 1 to 10 how willing would you be to use X-rays as your sole source of irradiation?

- Scale of 1 to 10

What concerns do you have when considering the switch from Cesium-137 irradiators to X-ray irradiators? (Select all that apply)

- Cost
- Maintenance
- Dose uniformity across a sample
- Accuracy
- Inconvenience (I.E. long installation process)
- Inconsistency with / Obstruction of current research projects
- No concerns
- Other (Specify)

Is there anything else you would like us to know regarding the topic?

- (Open Response)

Appendix D: Survey Responses

Response Options	Number of Responses	Percentage of Total
In what capacity have you worked with irradiators?		
Research	26	72.2%
Blood Bank Worker	2	5.56%
Radiation Safety Officer	7	19.4%
Health Physicist	1	2.78%
What process have you utilized irradiators for?		
Blood Irradiation	5	14.7%
Sterilization	2	5.88%
Animal/Cell Research	11	32.35%
Clinical Research	1	2.94%
Research	2	5.88%
Investigation of Dosimetric Quantities	1	2.94%
Radiation as a Perturbation	1	2.94%
Bone Marrow Irradiation	3	8.82%
Tumor Treatment	1	2.94%
Haven’t Used Irradiators	1	2.94%
Immune System Suppression	1	2.94%
DNA Damage Studies	3	8.82%
Human PBMCs	1	2.94%
Regulate the use for Blood Products, animals, and cell irradiations	1	2.94%

What level of accuracy do you require for your irradiations?		
<5%	6	17.1%
5-20%	9	25.7%
20-50%	0	0.00%
50-75%	1	2.86%
>75%	10	28.6%
N/A	9	25.7%
What types of irradiations do you perform?		
Cells	25	47.2%
Animals	22	41.5%
Blood Products	3	5.66%
Tissue	1	1.89%
Sterilization	1	1.89%
Caenorhabditis Elegans	1	1.89%
If animal, please specify cell type.		
Mice	8	36.4%
Bone Marrow	1	4.55%
Whole Body	2	9.09%
Intestinal Epithelium	1	4.55%
Rats	1	4.55%
Zebra Fish	1	4.55%
Splenocytes	1	4.55%
Caenorhabditis Elegans	1	4.55%
Model Organism	1	4.55%
Nematode	1	4.55%

Hematopoietic stem cell	2	9.09%
Progenitor cells in mouse	1	4.55%
NSG, C57/bl6	1	4.55%
Have you ever used an irradiator that utilizes Cesium-137 as its source?		
Yes	32	91.4%
No	3	8.57%
Have you ever used an irradiator that utilizes X-rays as its source?		
Yes	19	54.3%
No	16	45.7%
On a scale of 1-10, how willing would you be to use X-rays as your sole source of irradiation?		
1 (Unwilling)	7	20.0%
2	1	2.86%
3	7	20.0%
4	2	5.71%
5	0	0.00%
6	1	2.86%
7	2	5.71%
8	3	8.57%
9	2	5.71%
10 (Willing or already do)	10	28.6%
What concerns do you have when considering the switch from Cesium-137 irradiators to X-ray irradiators?		
Dose uniformity across a sample	19	21.8%
Accuracy	14	16.1%
Inconsistency with/	20	23.0%

Obstruction of current research projects		
Cost	8	9.20%
Maintenance	11	12.6%
Inconvenience (long installation process)	6	6.90%
Reliability	1	1.15%
No concerns	4	4.60%
Downtime vs Cesium	1	1.15%
Cost to dispose of Cesium	1	1.15%
Ease of use	1	1.15%
Different effects on bone marrow engraftment in mice	1	1.15%

Last Question: Is there anything else you would like us to know regarding the topic?

- Strongly would prefer to keep as Cesium137 for the reason above.
- I use a Cesium-137 irradiator to irradiate cellular blood products in a hospital blood bank. I support switching to a X-ray irradiator in the (hopefully near) future.
- The switch was aided by group pricing and the switch was pretty easy. The results for the blood bank were excellent. Some researchers were not keen on the switch because of the length of data acquisition from a history of using the same irradiator.
- This is a long-range process that requires close collaboration and buy-in from users. It is also not an inexpensive endeavor.
- I heard that X-ray based irradiators can be difficult to maintain, whereas Cs137 based ones can last decades with low maintenance
- I would be concerned how long the training takes and installation
- How X-ray irradiation compare to Cs-137
- radiation to plates or flasks etc.
- Our institution switched in 2019, and it's worked out well so far.
- In general, the researchers have been satisfied with the switch from Cs-37 to x-ray.
- I used a Faxitron at Umass Worcester to irradiate with zero problems.
- Maintenance is a big concern, Cs- 137 don’t suddenly stop irradiating the way an X-ray can.