Close the gaps, minimize risks. If not now, when?

**Successful Migration from Radioactive Irradiators to X-ray Irradiators in One of the Largest Medical Centers in the US**

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**Abstract:** This paper summarizes about 9 years of effort by Mount Sinai to successfully migrate completely from radioactive irradiators to x-ray irradiators without compromising patient care or research studies. All the effort by Mount Sinai to permanently remove the risk of malicious use of radioactive materials as Radiological Dispersal Device or dirty bomb is reviewed. Due to the unique characteristics of the cesium chloride ($^{137}$CsCl) used in irradiators, it is especially susceptible to be used as a dirty bomb. Mount Sinai originally had four of such irradiators. To reduce and eventually remove the risk of malicious use of radioactive materials, Mount Sinai in New York City has taken several steps. One of such measures was to harden the radioactive irradiators to make the radioactive materials harder to be stolen for malicious purposes. By increasing the delay time, the local law enforcement agency (LLEA) will have more time to stop the intruder. Another measure taken was to implement enhanced security in facilities having radioactive materials. We collaborated with the National Nuclear Security Administration and used state-of-the-art security equipment such as Biometric Access Control and 24/7 video monitoring. In addition, a remote monitoring system with alarms was installed and connected to LLEA for constant monitoring and possible intervention, if necessary, in a timely manner. The other measure taken was to limit the number of people who have access to such radioactive materials. We adopted a single person operator method and reduced the number of people having access from 145 people to only a few people. The adoption of such measures has reduced the risk significantly; however, the best way to remove the permanent risk of these radioactive materials that may be used for a dirty bomb is to use alternative technology to replace these high-activity radioactive sources.

In 2013, Mount Sinai purchased its first x-ray irradiator to investigate the feasibility of using x-ray irradiators instead of cesium irradiators for research purposes for cells and small mice. The results from comparison studies were promising, which led to the decision of permanent migration of all cesium irradiators to x-ray irradiators. As of January 2018, Mount Sinai successfully disposed all its $^{137}$Cs irradiators.

At this time, Mount Sinai, as one of the largest health care institutions in NY with about 50,000 employees, has migrated completely to alternative technology and removed the risk of malicious use of radioactive materials permanently. Health Phys. 117(5):558–570; 2019

**Key words:** operational topic; cesium; education, health physics; x rays

**INTRODUCTION**

History of cobalt-60 and cesium-137 irradiators

The commercial use of gamma irradiators began in the late 1950s with the use of radiation to sterilize health care products. The increased experience and confidence with that technology led naturally to the investigation of additional irradiator applications. Over time, novel irradiator designs were developed and optimized specifically for different applications, from food irradiation to materials processing.

A significant impetus to the creation of irradiators was the advent of nuclear reactors, which have the capability of producing radioisotopes. The gamma ray emitters, $^{137}$Cs and $^{60}$Co, quickly became the most popular radiation sources for medical and industrial applications. Both $^{137}$Cs and $^{60}$Co are produced in nuclear power reactors. $^{137}$Cs is a fissile isotope produced in the reactor fuel during operation. $^{60}$Co is a synthetic isotope produced via neutron activation of natural $^{59}$Co. Slugs or pellets made of natural $^{59}$Co are placed in a nuclear power reactor and undergo neutron activation for 1–2
years to produce $^{60}$Co sources. $^{60}$Co and $^{137}$Cs are the most suitable gamma radiation sources for irradiators because of the relatively high energy of gamma rays emitted and fairly long half-lives (5.27 y for $^{60}$Co and 30.1 y for $^{137}$Cs). Currently, nearly all industrial irradiation facilities employ $^{60}$Co as the source of radiation because of its easy production method and its non-solubility in water. The use of $^{137}$Cs has been limited to small, self-contained, dry-storage irradiators, used primarily for the irradiation of blood and for insect sterilization (IAEA 2006).

Over time, additional radioactive irradiators were built, and the kinds of applications that use gamma radiation steadily increased. Some applications of radioactive irradiators are sterilizations of health care products, sterilizations of food and seeds, and environmental applications such as wastewater and sludge treatment. Also, it showed an increased use in medical facilities to irradiate blood before transfusion as well as research irradiators in universities, medical schools, and national laboratories. Material processing also makes uses of irradiators where gamma radiation is used to treat polymers, like cables and tubing, for the purpose of property modification. Some of these irradiators operate for a single process, while others are used for multiple purposes. In recent times, the use of x-ray irradiators as a replacement for radioactive irradiators has been increasing.

**Goiânia accident 1987**

The Goiânia accident was a radioactive contamination accident that occurred on September 13, 1987, at Goiânia, in the Brazilian state of Goiás, after an old radiotherapy source was stolen from an abandoned hospital site in the city. It was subsequently handled by many people, resulting in four deaths. About 112,000 people were screened for radioactive contamination and 249 were found to have significant levels of radioactive material in or on their bodies.

The radiation source involved in the Goiânia accident was a small capsule containing about 93 grams of highly radioactive cesium chloride ($^{137}$CsCl) encased in a shielding canister made of lead and steel. The source was positioned in a container of the wheel type, where the wheel turns inside the shielding canister to move the source between the storage and irradiation positions. The International Atomic Energy Agency states that the source contained 50.9 TBq (1,380 Ci) when it was taken and that about 44 TBq (1200 Ci) or 87% of contamination had been recovered during the cleanup operation. Eventually, the important lesson learned was that less than 100 grams of CsCl powder resulted in more than 40 tons of radioactive waste. That incident was not an attack; it was an accident in 1987. Just imagine if that incident would happen in 2018 in a densely populated area; the result would be economically devastating (IAEA 1988).

Cesium chloride irradiators ($^{137}$Cs irradiators) and the security issues and National Academy of Sciences report and recommendations

$^{137}$Cs self-shielded irradiators have been used for many years for blood products, biomedical, and small animal irradiations. Approximately 10% of donated blood, about 3 million units per year (Sullivan et al. 2007), is irradiated in a production mode by blood centers and medical institutions largely to prevent transfusion-associated graft vs. host disease (TA-GvHD) for certain patients. Biomedical and small animal irradiations are performed mostly for research purposes at universities and hospitals (Dodd and Vetter 2009). $^{137}$Cs was selected for irradiation purposes because of its desirable single (662 keV, for unshielded photons) energy spectrum, moderate shielding requirements relative to some other radioisotopes (e.g., $^{60}$Co), long half-life, and relative low cost (byproduct of the nuclear irradiators).

In 2008, the US National Academy of Sciences (NAS) published a landmark report *Radiation Source Use and Replacement*, which examined the feasibility of replacing high-risk radioactive sources with less risky (and most likely non-isotopic) alternatives in order to forestall an act of radiological terrorism. The report expressed particular concern about the threat posed by the continued use of one radioactive source—cesium chloride—whose unique characteristics make it especially susceptible to being used by terrorists. The report recommended that government policies be enacted that would lead to the substitution of less hazardous technologies (Pomper et al. 2014).

Unfortunately, there seems to be no liability insurance coverage provided to compensate the indirect damage from malicious use of a $^{137}$Cs irradiator. Current insurance plans only cover the physical damage directly resulting from the explosion of a dirty bomb. The contaminated items and the cleanup cost are not covered by the insurance. This could be a significant financial burden to the institutions that possess substantial quantities of radioactive sources if these are used maliciously. Also, there is not yet a precedence case on how to prevent or stop the cyber-attack on the $^{137}$Cs irradiator’s security system. The majority of security connections between the irradiators and security command centers as well as the local law enforcement agencies (LLEAs) are connected through the internet. The breach of a security system could give the terrorists longer time to take the sources out.

The US NAS report recommended that government policies be enacted that would lead to the substitution of less hazardous technologies. The Academy’s conclusions were partially embraced by the United States government. In 2010, an interagency Task Force on Radiation Protection and Security...
submitted its quadrennial report to the President and Congress. The report emphasized the security measures that have been implemented to protect existing, risk-significant, radiological sources. It concluded that for cesium chloride “immediate phase-out would not be feasible because the sources are extensively used in a wide range of applications in medicine, industry, and research” (US NRC 2010). However, it concluded that a gradual stepwise phase-out could be feasible as alternatives become technologically viable and if disposal pathways are identified. It also noted that “While alternatives exist for some applications, the viability, relative risk reduction achievable, and state of development of these alternatives varies greatly.”

Global effort

France started in 2006 with a 10-y plan to remove the $^{137}$Cs irradiators. They had 30 irradiators and they have completely replaced them with x-ray irradiators. Norway finished replacing all 13 $^{137}$Cs blood irradiators with x-ray blood irradiators in 2015. Japan has started replacing the $^{137}$Cs blood irradiators 20 years ago, and 80% of them were replaced by x-ray irradiators (NTI 2010).

How real is the risk of radioactive dispersal device?

There have been many attempts globally to use radioactive materials in a dirty bomb or weapon of mass disruption (WMD). In December 1998, in Chechnya, a radioactive container filled with radioactive materials was attached to an explosive device found near a railway. In June 2002, Jose Padilla, a US citizen with links to Al-Qaeda, was arrested in Chicago for planning to build and detonate a dirty bomb. On January 2003, based on the evidence uncovered by the British Intelligence from Afghanistan, it was concluded that Al-Qaeda had succeeded in constructing a small dirty bomb. In August 2004, Dhiren Barot was arrested for planning to blow up the New York Stock Exchange with a dirty bomb. According to the Pool Re report of December 2016, under the title of “Terrorism Threat and Mitigation Report” by Ed Butler, the head of the Risk Analysis at Pool Re, the international terrorist threat (including the risk of dirty bomb attacks) level to UK remains at SEVERE (attack is highly likely) despite no major attacks recently.

There have been numerous articles showing that ISIS (known as DAESH in Europe) is trying to get their hands on high activity radioactive sources to make radioactive dispersal devices (RDDs). Mount Sinai realized that the dispersion of a $^{137}$Cs irradiator source would cause a disastrous outcome if someone uses it maliciously against the public, especially in a densely populated area like New York City (NYC). In the last 20 years, there have been at least 12 terrorist attacks and at least 20 attempts in NYC, including 4 attacks in the last 2 years. No doubt that NYC is the terrorist target of choice in the US. That is why we need to reduce and remove the risk from all aspects to keep our loved ones safe.

Risk analysis for Mount Sinai

Mount Sinai Medical Center was founded as Jew’s Hospital in New York in 1852. The name was changed to Mount Sinai Hospital in 1866 to reflect the fact that it serves an integral part of the general community. In the late 1950s, the hospital began plans to establish its own medical school, an unusual move for a hospital. With its chartering in 1963, Mount Sinai School of Medicine, now called the Icahn School of Medicine at Mount Sinai, became the first medical school to grow out of a non-university in more than 50 years. The Mount Sinai Health System, formed in September 2013, combined the operations of Continuum Health Partners and the Mount Sinai Medical Center. The Mount Sinai Health System is structured around seven hospital campuses and the Icahn School of Medicine at Mount Sinai. The seven hospitals are Mount Sinai Beth Israel, Mount Sinai Brooklyn, The Mount Sinai Hospital, Mount Sinai Queens, Mount Sinai West (formerly Mount Sinai Roosevelt), Mount Sinai St. Luke’s, and New York Eye and Ear Infirmary of Mount Sinai. Mount Sinai Health System hires close to 50,000 employees and is one of the largest health care institutions in the US (Mount Sinai Website).

As part of risk analysis for Mount Sinai, there are several specific points that makes Mount Sinai a potential soft target for the malicious use of high activity radioactive materials:

- **Location in NYC and near subway stations:** Terrorist groups constantly threaten to attack public transportation. They attacked trains in Spain and UK. If attacks happen in NYC, with or without radiation, Mount Sinai expects to accept many injured individuals. There have been at least 20 known terrorist attempts since 9/11 towards NYC. Mount Sinai is located in NYC with at least 7 to 8 subway entrances located within less than a mile.

- **Hospital Entity:** “Soft targets” are relatively unprotected or vulnerable to terrorist attacks. Typical soft targets are civilian sites where people congregate in large numbers, and hospitals are one of the typical soft targets (Forest 2006). Terrorist groups would target hospitals to delay the response to mass casualties. In 2017 there was an attack on a hospital in Afghanistan where a terrorist group dressed as doctors and killed 55 people. Mount Sinai is a major hospital in NYC.

- **RDD ingredient:** On September 11, 2001, a terrorist group used our own planes as missiles to attack our own cities. Is there any radioactive source in Mount
Mount Sinai that could be used by terror group? Mount Sinai had originally 4 $^{137}$Cs irradiators. Two of the irradiators were disposed in 2016 through the Off-site Source Recovery Program (OSRP). The remaining radioactive sources could have been used as dirty bombs, but fortunately we were able to remove those in January 2018.

**Jewish entity:** There have been many terrorist attacks on Jewish entities. To name a few, a bomb attack in Morocco in May 2003 killed 41 people in 5 sites including the Jewish Cultural Center. On November 15, 2003, two trucks carrying bombs slammed into the Beth Israel and Neve Shalom synagogues in Istanbul, Turkey, and exploded. The explosions devastated the synagogues and killed 23 people. In 2009, the FBI arrested four suspects in an alleged plot to bomb Bronx synagogues and to shoot down planes (Daly et al. 2009). In January 2015, an Islamist gunman killed three customers and an employee at the Hyper Cacher kosher supermarket in Porte de Vincennes in the east of Paris, in the aftermath of the assault on the offices of the Charlie Hebdo magazine (Rayman 2015). Mount Sinai is a Jewish entity.

**MOUNT SINAI’S ACTION PLAN**

Mount Sinai was aware of the risk that the $^{137}$Cs irradiator sources might be used maliciously by the terrorist group, which would pose a great danger to the public. Therefore, since 2010, Mount Sinai has planned and collaborated closely with the US government agencies as well as local agencies, such as the NYC Department of Health and Mental Hygiene (NYCDOHMH), New York Police Department (NYPD), and US Department of Energy National Nuclear Security Administration (NNSA), to minimize the risk of malicious use of radioactive materials in quantities of concern. Mount Sinai adopted a three-phase plan to eventually remove the $^{137}$Cs irradiators from all the campuses. The three phases are:

- **Phase 1**—Prepare to respond to possible Radiological Incidents: Get ready for the worst case scenario;
- **Phase 2**—Reduce the risk: Harden Security, Limit Access, FBI background check on staff with access; and
- **Phase 3**—Remove the risk: Use Alternative Technology and dispose all Cs-137 irradiators

The details of each phase are described in the following sections.

**Preparation to respond to possible radiological incidents**

**Proper radiation equipment.** Mount Sinai purchased proper radiation equipment such as portal monitors, area monitors, personal electronic radiation dosimeters, the identiFiNDER (FLIR® Systems, Inc. 27700 SW Parkway Ave, Wilsonville, OR 97070), and decontamination kits for possible use (see Fig. 1).

The personal electronic radiation dosimeters are distributed to the security staff and emergency response staff for daily use to detect the presence of any abnormal radiation level in the medical center. The staffs were trained to use the dosimeter and respond to any abnormality detected. The personal electronic radiation dosimeter is the same model used by NYPD and local regulatory agencies so that in real emergency information could be easily exchanged. The area monitors along with alarms were installed in the entrances in Mount Sinai Medical Center to detect any abnormal exposure level. These radiation alarms are checked on a regular basis for proper operation.

**Drill with Fire Department and Police Department.** To prepare for accepting patients contaminated with radioactive materials in a mass casualty event, the radiation safety office at Mount Sinai has developed Standard Operating Procedures (SOPs) regarding emergency handling of mass casualty radiation accident cases. The Radiation Safety Office staff took part in periodic drills in Mount Sinai Medical Center. The content of the drills includes setting up check points to survey contaminated patients coming in the medical center for help, decontaminating patients, and treating patients who receive high radiation doses. Mount Sinai has designated decontamination areas and showers. In a real mass contamination incident, people may be directed to a large area for triage close to the emergency room where contamination screening can be performed (see Fig. 2).

![Portal monitors which can be used to survey personnel contamination monitoring and meets the FEMA standard for Emergency Response Portal Monitoring. (Middle) The personal electronic radiation dosimeter distributed to our security personnel to detect abnormal radiation level. (Right) identiFiNDER is used to identify unknown radioisotopes.](image-url)
Phase 2—Reduce the risk: harden security, limit access, FBI background check on staff who have unescorted access and pre-arranged plan with NYPD

Mount Sinai Started Phase 2 to reduce the risk in 2008 as the NAS made recommendation about the security of high activity radioactive sources. Below are the measures taken by Mount Sinai to reduce the risks.

Pre-arranged plan with NYPD. To prepare for an actual or attempted theft, sabotage, and diversion of radioactive materials in quantities of concern, Mount Sinai Medical Center developed a pre-arranged plan with NYPD. The pre-arranged plan includes the procedure, the important contact information, the risk assessment form, and the radioactive material exposure log.

Limit access. At one point in 2008, there were about 145 researchers who had access to the research irradiator 24/7. These individuals were mostly graduate students and post-doctoral fellows. The machine broke down very often. Mount Sinai decided to introduce a single-person operator to irradiate animals and cells for all the researchers. We limit the unescorted access to the research irradiator to a primary individual as well as a backup person. The single operation was in place from 2008 to 2018 and is no longer needed as all researchers are using x-ray irradiators.

In the Blood Bank, because Mount Sinai’s blood bank is a 24-h operation, there are 3 shifts a day. It used to be all the staff in blood bank could access the irradiator. After 2008, we authorized the unescorted access to the blood irradiator only to the managers and a few senior staff in each shift.

A few management staff in Mount Sinai’s Security Department as well as Radiation Safety staff underwent FBI background check and were given unescorted access to these facilities to respond to any emergencies.

Background Investigation. For people who seek the authorization of the unescorted access, Mount Sinai conducts a very strict background investigation. The background check includes the identification verification, the reputation review, the employment history of the last 7 years, the FBI background check of criminal history, and the FBI finger printing process. The purpose of such strict background investigation is to make sure that people having unescorted access to the irradiators are trustworthy and reliable. The individuals who were granted the unescorted access are subject to the re-investigation every 10 years until they no longer need the access to the irradiators.

Harden Security-Collaboration with US-DOE-NNSA. Mount Sinai collaborated with the US Department of Energy (DOE) National Nuclear Security Administration (NNSA) to enhance the security of irradiators through the Global Threat Reduction Initiative (GTRI) program, which is now known as the Office of Radiological Security (ORS). Mount Sinai was the first medical center to be connected to Lower Manhattan Security Initiative (LMSI) of the NYPD. With the enhancement of security, it delays not only to break into the irradiator facility, but also allows the law enforcement agencies to have more time to stop the malicious activity. The RMS is checked on a regular basis to make sure that it is working properly.

Phase 3—Remove the risk: use alternative technologies and dispose all radioactive irradiators

After phase 2, the risk has already been reduced significantly. Moreover, with the development of the non-isotopic alternative technologies, the $^{137}$Cs irradiators could be replaced and removed from medical and research facilities. Therefore, Mount Sinai decided to collaborate with the US DOE NNSA to proceed with comparison studies and permanently remove the $^{137}$Cs irradiators.

Off-site Source Removal Program (OSRP) and Cesium Irradiator Replacement Project (CIRP) Program. The US DOE’s National Nuclear Security Administration (NNSA) Office of Radiological Security (ORS) is working with domestic users of $^{137}$Cs irradiators who are interested in converting to viable non-radio-isotopic alternatives. The CIRP, offered by ORS, provides qualified sites who are interested in making the switch with a financial incentive towards the purchase price of a new non-radio-isotopic device, as well as the removal and disposal of the cesium.

**FIG. 2.** (Left) The drill simulated a radiological incident with Radiation Safety staff in Mount Sinai. (Middle) Showers with drop off curtains (hot and cold) for decontamination. (Right) FDNY truck parked inside of Mount Sinai during the drills.
irradiator. CIRP was launched in 2014, and is supported by the United States’ commitment to facilitate the replacement of 34 $^{137}$Cs irradiators with non-radio-isotope alternatives by 2020. Qualified participants will receive:

- Removal and disposal of the $^{137}$Cs irradiator, saving the site approximately $200K per irradiator;
- A limited financial payment towards the purchase of the new non-radioisotope device, up to 50% of the purchase price. The payment will be disbursed when the cesium device has been removed and the non-radioisotope device has been installed; and
- Training, warranty/maintenance agreement costs, and spare part costs were the responsibility of the site.

For further information on the CIRP and to discuss whether and how CIRP could work for your site, please contact ORS at ORSInfo@nnsa.doe.gov.

**Feasible non-isotopic alternative technologies: blood irradiators.** In 2010, an inter-agency Task Force on Radiation Protection and Security submitted its quadrennial report to the US President and Congress. The Task Force report noted that for blood irradiation x-ray technologies are cost competitive with radionuclide technologies on an annualized basis although concerns remained about their throughput and reliability. Other technologies, such as linear accelerators (LINACs), could be used for blood irradiation in addition to their principal use in cancer treatment.

We found out that there were two x-ray blood irradiators for human use approved by the US Food and Drug Administration (FDA) available in the market—Raycell, manufactured by Best Theratronics and Rad Source’s RS3400. These two x-ray blood irradiators meet the American Association of Blood Banks (AABB) recommendation that a radiation dose of 25 Gy (minimum 15 Gy) for treating blood in order to prevent GVHD. There is one published study that concludes that small differences in RBC membrane permeability are found between gamma-irradiated and x-ray-irradiated units. However, these differences are not likely to be clinically important (Janatpour et al. 2005). In 2011, the UK guideline by the British Committee for Standards in Haematology blood transfusion task force, concluded that blood x-ray irradiation was recommended as a suitable safe alternative to gamma ray irradiation (Treleaven et al. 2011).

**Feasible non-isotopic alternative technologies: biomedical research irradiators.** In 2013, a new research building including an animal facility was opened in Mount Sinai. The researchers decided to acquire a new biomedical irradiator because the animal facility is far from the existing $^{137}$Cs irradiator facility. We started to investigate the options. At that time, there were not that many published papers available about the comparison of x-ray irradiators and $^{137}$Cs irradiators. There was one paper published by B. R. Scott that indicated that x-ray sources such as the X-RAD 320 Unit can be used as successfully in studies of radiation cytotoxicity in culture as in the case of $^{137}$Cs sources (Scott et al. 2012). Mount Sinai made a decision to get an x-ray irradiator for preparation of the final transition to x-ray irradiators from $^{137}$Cs irradiators. There were several options in the market for biomedical irradiators. Among the various models, the maximum energies vary from 160 kVp to 450 kVp. Other differences among the irradiators that should be considered include the irradiation chamber size, the irradiator size, the cooling method, and the accessories of the irradiators, etc. Unlike the blood irradiators, which are FDA approved, there is not a criterion to determine which models of x-ray biomedical irradiators to acquire for research purposes. Also, as previously mentioned, there are not many published studies showing that the x-ray has equivalent effect on cells and animals in all the applications compared to $^{137}$Cs irradiators. Mount Sinai eventually purchased a RadSource RS 2000 irradiator. With the new x-ray biomedical research irradiator, Mount Sinai’s physicists and researchers started to work together to do comparison studies to see the feasibility of completely phasing out the $^{137}$Cs research irradiators and to replace them with x-ray irradiators.

**DOSIMETRY MEASUREMENTS**

**Radiation dose**

Damage from ionizing radiation is related to the absorbed dose, which is defined as the amount of ionizing radiation energy absorbed per unit mass of irradiated material. Absorbed dose is a macroscopic concept which is correlated to biological damage at the tissue and organ level. At the sub-cellular level biological damage can occur from the breaking of intramolecular bonds in biologically relevant molecules such as DNA (Cember and Johnson 2008). There is a wealth of literature on effects on cells in culture that show absorbed dose for a variety of cellular level endpoints such as cell survival, mutations induced by radiation, and neoplastic transformation induced by radiation is a good approximation and therefore relative biological effectiveness (RBE) is useful. An example among many, by Spadinger and Palic (1992), actually looked at the RBE for several types of radiation for two well-known cell lines on the tissue level; the number of such intramolecular breaks in the tissue is proportional to the radiation absorbed dose.
Factors that affect dose.

Dose distribution: One of the factors that affect the outcome from irradiation is the dose distribution in the irradiated specimen. During irradiation, photons enter a specimen and deposit energy. The flux of photons available for absorption decreases with depth since photons become absorbed as they penetrate the specimen. This creates non-uniformity in the dose distribution of the specimen, with a higher dose near the surface. In general, as photon energy increases the amount of attenuation through the specimen decreases. This means that higher energy photons typically produce a more uniform dose distribution. This effect is more pronounced for thicker specimens and for photon energies that are very different.

Non-uniformity can be reduced through a variety of ways. The specimen could be rotated with respect to the incident radiation so that the specimen is irradiated from multiple sides. This is the principle used to justify turntable rotation in some $^{137}$Cs irradiators or “ferris-wheel”-like rotation in some blood irradiators and has been adopted in various forms as an option for some newer x-ray irradiators. Another method of increasing the dose uniformity is to surround the specimen with a block of photon reflective material. This method has been used in some research x-ray irradiators.

RBE: The relative biological effectiveness (RBE) is defined as the ratio of the doses required by two radiations to produce the same biological effect. RBE is typically defined as the ratio of the dose required to produce a biological effect (e.g., skin reaction and death of mice) for a given radiation type and energy (e.g., $^{137}$Cs gamma rays) to the dose required to produce the same effect using a standard radiation type and energy (e.g., 250 kV x rays):

$$\text{RBE} = \frac{\text{Dose of Standard Radiation}}{\text{Dose of Test Radiation}}$$

RBE depends on the radiation type and energy of both the standard and test radiation, and the biological effect being studied. Therefore RBE is inherently an empirical value which requires actual experimental data to quantify. In Fig. 3 the general relationship between LET (linear energy transfer) and RBE is shown.

The important take away from the relationship shown in Fig. 3 and in the list of LETs in Table 1 is that in the energy deposition region between 0.1 keV $\mu$m$^{-1}$ and almost 10 keV $\mu$m$^{-1}$ the RBE is 1. $^{60}$Co radiation has an average LET of 0.2 keV $\mu$m$^{-1}$ while $^{137}$Cs radiation has an average LET of 0.91 keV $\mu$m$^{-1}$ and conventional 250 kV x-ray irradiation has an average LET of 2.0 keV $\mu$m$^{-1}$. They all lie close to the LET of 1.0 keV $\mu$m$^{-1}$ on the log scale in Fig. 3 that has an RBE of 1.0 (Hall and Giaccia 2012). To be clear, we are not talking here about x rays below 55 kV that have significantly different RBEs and very different dose depth absorption characteristics. We are talking about energetic, low LET radiations used to deposit dose as evenly as possible through everything from single cells to whole small animals.

Due to the complexity involved with performing RBE measurements for every possible radiation and every possible biological effect, the quantity “RBE” was simplified for the purposes of radiation protection to use a similar term called the “radiation weighting factor” (W$_{\text{R}}$). The biological effects of most interest to radiation protection are stochastic effects (i.e., cancer incidents) produced by irradiating human tissue. For this particular biological effect, photons of different energies have approximately the same RBE, and therefore the radiation weighting factor is equal to 1 for photons of all energies. It should be noted that this does not imply that the RBE for all photon energies is the same, since RBE must always be defined in terms of the biological effect being observed.

Repair. Repair mechanisms also play a key role in radiation biology. Some biological effects caused by a dose of ionizing radiation may be repaired over time (e.g., DNA damage). In general, the longer the time between subsequent damage events, such as two single
strand breaks, the greater the likelihood of a successful repair. This principle is used in radiation oncology where a single large radiation dose is split into smaller fractions delivered over a longer period of time to allow for repair of healthy tissue (fractionation). The effect of repair mechanisms can also be seen within a single dose, where lower dose rates can have an increased repair. For instance, studies on dose-rate effects imply that there is a repair mechanism to correct genetic lesions. Animals exposed at low dose rates show mutation rates that are one-fifth to one-tenth the mutation rate observed at high dose rates. This dose-rate dependence implies a repair mechanism that is overwhelmed at high dose rates. Therefore, the dose rate used during irradiation is a factor that must be considered in evaluating the efficacy of irradiators. Decayed $^{137}$Cs irradiators may have a lower dose rate which might impact the repair of cells. Generally, repair becomes a significant factor if the dose rate falls below 0.5 to 5 cGy per minute depending on the endpoint under study. To be conservative and for practical purposes, it is probably not recommended to go below 50 cGy min$^{-1}$ (0.5 Gy min$^{-1}$) (Hill et al. 1984).

**Dose variation**

The dose distributions in the irradiators were provided by the manufacturers at the commission of each irradiator. In Fig. 4 the dose distribution for the $^{137}$Cs irradiator (left) an x-ray irradiator (right) are shown. The $^{137}$Cs irradiator dose distribution diagram is a vertical plane that is parallel to the source, positioned in the animal irradiation setup. The x-ray irradiator dose distribution diagram is a horizontal plane that is parallel to the source, positioned in the animal irradiation setup. The dose distribution in the x-ray irradiator is more homogeneous than in the $^{137}$Cs irradiator at the location (level) for mice irradiation. There are large differences in source geometry, essentially between the point source (x-ray) and the line source ($^{137}$Cs). This is a very important point because in $^{137}$Cs irradiators, the sample is rotated during the irradiation and if the mice move closer to the edge of the cage, then it will give completely different results than mice in the center of the cage. In an x-ray irradiator there is generally no rotation of samples although some newer machines are introducing rotating cages designed to give more dose consistency with depth in the x-ray beam.

Some $^{137}$Cs irradiators have two sources: one below and one above the pancake shaped irradiation chamber. While this potentially avoids more dose on one side than the other, it should be remembered that the 100% dose point is in the center between the two sources. As one gets closer to or touches the bottom of the chamber where the mice would normally be placed, the dose can be 5 to 10% higher than the nominal dose rate measured in the center point. It is extremely important to measure (know) the absorbed dose rate at the exact location where your specimen is irradiated in the $^{137}$Cs irradiator before doing a comparison with a new x-ray machine. In an x-ray machine, it is critical to measure dose distribution and dose rate at the center point of exposure as this absolutely varies with distance from the source and distance from the central axis of the x-ray beam. By using filtration and collimation x-ray machine, manufacturers have improved the dose distribution over a significant area at a given distance as shown in the right panel of Fig. 4.

**Percent depth dose measurement**

The British Journal of Radiology published supplement 25, 1996 which shows the results of Monte Carlo calculations of the Percent Depth Dose (PDD) curves (Fig. 5). The quantity percent depth dose may be defined as the quotient, expressed as a percentage, of the absorbed dose at any depth $d$ to the absorbed dose at a fixed reference depth $d_0$ along the central axis of the beam.

We have measured the PDD curves using our own irradiators. The PDD curves were measured with EBT 2/EBT 3 films sandwiched between different thicknesses of solid water phantom slabs and in small rodent phantoms in JL Shepherd Mark I-68 $^{137}$Cs irradiator and RS2000 x-ray irradiator (160 kVp, 25 mA), respectively. The measurements in small rodent

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**FIG. 4.** The dose distribution in the irradiators provided by the manufacturers. (Left) The isodose map in JL Shepherd Mark I-68 $^{137}$Cs irradiator at location 3 measured with a film and provided by JL Shepherd. (Right) The dose rate measurements in RS2000 x-ray irradiator at level 1 with RAD+ reflector.
phantoms were performed by Mark Murphy from Pacific Northwest National Lab (PNNL) using Mount Sinai’s irradiators. The PDD measurements show very similar curves for 160 kVp x ray, 320 kVp x ray, and $^{137}$Cs (662 keV) in both solid water phantoms and small rodent phantoms, particularly in the first 2 to 4 cm of depth in water that is relevant to cells, tissues, and small whole animal exposures (Fig. 6).

**COMPARISON STUDIES**

Now that we have confirmed in physics, we asked our researchers to do the comparison studies. The researchers in Mount Sinai use the irradiators for many different purposes (Fig. 7). The major applications include bone marrow ablations in mice, suspension of cell cycle, and treatment of tumors implanted in mice. We have some researchers who did comparison studies for different applications to see if x-ray irradiation can give similar results as $^{137}$Cs irradiation or what the dose is for x-ray irradiation to have equivalent effect as in $^{137}$Cs irradiation.

**Bone marrow ablation**

Miriam Merad’s lab compared the bone marrow ablation on 35 mice with x-ray whole body irradiation. The dose was 6 Gy each time, two times with 12- to 24-h intervals, and total dose 12 Gy. Only 1 mouse died out of 35 mice for 50 d survival. The result of the chimeras shows that all recipients were around 90% of donor origin, which is similar to $^{137}$Cs irradiation. Merad’s lab performed another bone marrow ablation experiment, and the result shows 100% of donor origin, which is also similar to the result of $^{137}$Cs irradiation. Gibson et al. also concluded that both the x-ray and $^{137}$Cs sources used in this experiment provided similar results with regard to long-term peripheral blood reconstitution after bone marrow ablation.

**Figure 5.** PDD plotted from data in BJR Supplement 25 (1996), for three x-ray qualities and for $^{137}$Cs and $^{60}$Co. For all the following parameters apply: $W = 10$ cm, SSD = 50 cm.

**Figure 6.** (Left) The PDD curves comparison for 160 kVp x ray (RS2000) and $^{137}$Cs (JL Shepherd Mark I-68). The PDD curves measured with EBT 2 films sandwiched solid water phantoms. (Right) The PDD curves measurements comparisons for 320 kVp x ray (X-RAD 320) and $^{137}$Cs (JL Shepherd Mark I-68). The PDD were measured with EBT 2 films sandwiched in small rodent phantoms.
Cell irradiation

Heeger’s lab grows human B cells on irradiated human fibroblasts feeder cell layers. The standard irradiation dose for this procedure using \(^{137}\text{Cs}\) irradiator is 43 Gy, and Heeger’s lab compared the results of various doses of x-ray to find the equivalent effect. The results indicate that 20–60 Gy x-ray has equivalent effects to the standard of 43 Gy \(^{137}\text{Cs}\) irradiation, and that x-ray doses above 80 Gy impair fibroblast and B cell growth.

Brody’s lab assessed the effect of irradiation on survival of A20 lymphoma cell line. They found that for x-ray irradiation, apoptosis is induced in a dose dependent manner, increasing from 25% at 9 Gy to 60% at 75 Gy, and doses over 75 Gy did not show a further increase in apoptosis induction.

Mice brain irradiation

Hadjipanayis’ lab did experiments of brain irradiation on 12 mice (other body parts were spared). The dose was 10 Gy (5 Gy each time, 48-h interval). 12 mice were exposed and all survived 30 d, which is similar to the result of \(^{137}\text{Cs}\) irradiation.

Disposal of radioactive irradiators

Mount Sinai had four \(^{137}\text{Cs}\) irradiators. The first blood cesium irradiator was disposed in October 2016, and the first biomedical \(^{137}\text{Cs}\) irradiator was disposed in December 2016. The remaining one blood irradiator and one biomedical irradiator were disposed in January 2018. Mount Sinai currently has no \(^{137}\text{Cs}\) irradiators, it has two biomedical x-ray irradiators and one blood x-ray irradiator. The disposal arrangement required collaboration of many departments within the institution (Radiation Safety, Blood Bank/Animal Facility, Security, Engineering, Loading Dock, Emergency Room) as well as with the regulatory agencies, Police Department, Highway Patrol, and office of emergency management, etc.

One particular situation that we experienced during the removal was the elevator capacity. Although during the planning of the removal we had checked the maximum capacities of the elevators to be used and confirmed with the elevator engineer that the elevator was capable for this operation, the elevator got stuck in the elevator well and would not move upward. The maximum capacity of the elevator was 6,500 pounds, and the weight of the irradiator to be removed was 6,000 pounds. Eventually, the elevator engineer had to manually bring up the elevator from the basement to the loading dock level inch by inch. This problem delayed the operation for 3 hours. Our speculations were the computer program prohibited the move due to the weight, the capacity of the elevator decreased due to aging, or the capacity was not marked correctly. To avoid this situation, we suggest the institutions to use elevators with a capacity of more than 120% of the irradiator weight and have the elevator engineer standby to operate the elevator during the operation. Otherwise, please discuss with the contracted technicians to see if they can dissemble the irradiator without decreasing the shielding to reduce the weight.

Steps of the disposal of radioactive irradiators

From source registration to source transferred:
1. Register the source on National Source Tracking System (NSTS) and OSRP
2. Set up the removal date with LLEA and other involved agencies.
3. Set up a few conference calls and a walk through for confirmation of details. Make sure you have a back up date if weather does not permit. Make sure elevator engineer is standby.
4. Make sure that licensing paperwork and transferring ownership of source paperwork are signed by appropriate personnel on the day of source removal.
5. Orchestrate for security enclosure removal if necessary.
6. Make sure that you get notified when the source is delivered to the final destination. Prepare the NRC forms for license verification and source transfer. Obtain a copy of the T&R letter for the personnel participate in this operation.

On the day of source removal:
1. Radiation Safety contacts LLEA for the operation. The RMS system is disconnected to LLEA.
2. The truck arrived at the institution.
3. The riggers unload the equipment.
4. The riggers/technicians unbolt the irradiator, removed the housing of the irradiator if necessary.
5. The irradiator is moved from the room to the loading dock, and further loaded on the truck.
6. When the irradiator is in the truck, the shippers/technicians survey the truck, and label the truck.
7. The local Police Department contacts the Port Authority, and when the route was cleared for the truck to pass, the police cars escort the truck to leave the institution.

MOUNT SINAI’S DECISION-MAKING ON PROCUREMENT OF X-RAY IRRADIATORS

There are a few factors that Mount Sinai considered when choosing an x-ray irradiator for purchase. The factors included FDA approval (for blood irradiators), the maximum energy, the irradiator chamber size (to have large throughput), the irradiator size (considering our space is limited), the self-cooling system, the add-ons (collimators, adjustable shelves, etc.), the price of the machine and the warranty cost, the renovation cost, the downtime, and the experiences of other users.

We first searched on-line for the available machines and narrowed down to 2 to 3 models. We invited the manufacturer representatives to Mount Sinai to demonstrate their machines, X-RAD320. After we invited the manufacturers to demonstrate their machines, X-RAD320 was chosen for the following reasons:

- Energy: up to 320 kVp.
- Irradiator chamber size: One of the biggest in the market.
- Irradiator size: fits our room.
- Self-cooling system.
- The add-ons: dose measurement exposure control, motorized specimen shelves, adjustable collimation fixtures.
- Price of the machine and the warranty cost.
- Lower room renovation cost.
- Shorter downtime: the company is in Connecticut, and within two hours they can come to Mount Sinai, so we expect a quicker fix if the machine needs repair.
- The review from other users: This X-Rad series irradiator is one of the bestsellers in the world.

OPERATIONAL MANAGEMENT

Blood irradiator

Mount Sinai Blood Bank staff conducted the validation procedures before using the x-ray irradiated blood on patients. About 900 units of x-ray irradiated blood were used on patients in the first month. During the first few weeks of using a new x-ray irradiator, it is expected that some “faults” would occur during the irradiation due to parts that are not fully conditioned. The manufacturer suggests that if there are three interruptions during one irradiation cycle, then the blood cannot be used as irradiated blood. Mount Sinai Blood Bank staff keeps a record of every time a fault occurs and noticed that the occurrence of the faults has decreased a lot since the beginning, and there have never been more than 3 interruptions in one cycle of irradiation so far. In fact, about 100 bags of blood were irradiated in 1 day to evaluate the machine under stress conditions, and operation went smoothly. The Blood Bank staff are satisfied with the operation and the throughput of the x-ray irradiator.

- RS3400 in Mount Sinai has been used for irradiating more than 9000 units of blood; no issues were prompted so far.
- RS3400 were stressed tested to irradiate more than 100 units per day, no issues were found.

Biomedical research irradiator

Researchers at Mount Sinai conducted the comparison studies for their own protocol adjustments. As the results mentioned in the previous section, the researchers found
similar x-ray irradiation outcomes to using the $^{137}$Cs irradiator in bone marrow ablation. For cell irradiation, the researchers created a calibration curve for the x-ray irradiation on different cell lines to find the dose that corresponds to the effect they desire. When managing the x-ray irradiator, it is important to make sure the cooling system is working well to avoid x-ray tube damage. We had an issue with the water cooling system during 2017. The error message popped up stating tube overheating. The manager of this unit contacted Precision X-ray and the company sent a technologist to see what was wrong with the unit. The technologist found out that there was cooling system because the tube was clogged. Eventually, a filtration system was installed to filter the cooling water. The machine had no issue after the fix.

We encourage all current researchers in research institutions that intend to migrate to alternative technologies to conduct comparison studies to prepare themselves for the final disposal of $^{137}$Cs irradiator. The researchers should collaborate with the medical/health physicists to plan for the comparison studies and the creation of future protocols using x-ray irradiators.

CONCLUSION

In this report, we summarized the effort we have made since 2010 to reduce and eventually remove the $^{137}$Cs irradiators in collaboration with many other institutions, regulatory agencies, law enforcement agencies, and US government agencies. Because the reliable alternative technologies are available now, we do believe that phasing out the $^{137}$Cs irradiators will eliminate the risk of using the high activity radioactive sources as possible weapons of mass disruption (WMD). We do appreciate the help of the US government OSRP program as well as the US-DOE-NNSA during the last 8 years, and we highly recommend all institutions to take advantage of the help these agencies offer. Some final points:

- $^{137}$Cs was not engineered for irradiation purposes; rather it was one of the by-products from nuclear power plant operation.
- The dose distribution in an x-ray irradiator is much more homogeneous than in a $^{137}$Cs irradiator.
- The dose deviation in an x-ray irradiator is much smaller than in a $^{137}$Cs irradiator.
- X-ray irradiators will not be covered under 10CFR part 37 regulations, and therefore there will not be any need to have any FBI background check on the staff incurring security cost and licensing cost.
- Institutions should use the US government program called “Off-site Source Recovery Program” to dispose of high-activity $^{137}$Cs sources. In the near future, these sources may become commercially disposable and it may then cost about $200,000 to dispose of each $^{137}$Cs irradiator.
- An institution’s leadership and management should check their insurance coverage very carefully for radioactive decontamination cost from a possible dirty bomb incident. They must remember from the experience in Brazil that 93 grams of cesium chloride powder resulted in more than 40 tons of radioactive waste.
- The governments of Norway, France, and Japan must be commended for their decisions to remove such sources from their societies. Perhaps this is one way we could help to fight and reduce the risk of malicious use of high activity radioactive sources.
- It is recommended to get a self-cooling and self-shielded x-ray irradiator.
- If possible, we recommend to setup for the manufacturer to be able to remotely see the error messages on the research irradiator to reduce the down time.

- For x-ray blood irradiators, it is recommended someone from the Clinical Engineering Department or the operators go to the company and get training on how to troubleshoot the irradiator.
- For x-ray blood irradiators, an air conditioned room is preferred; otherwise, you can use a fan or portable AC to maintain the room temperature and facilitate the heat dissipation from the irradiator.
- For x-ray research irradiator, make sure the water supply is clean and install a pre-filter for water intake.

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Migration from radioactive irradiators to x-ray irradiators

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