

# Hospital radioactive waste: public health implications and epigenetic consequences

## Abstract

**Background:** Radioactive waste generated in hospital settings, including diagnostic and therapeutic procedures, poses both immediate and long-term health risks. Emerging evidence links even low-dose exposures to epigenetic modifications, which may influence disease susceptibility across generations.

**Objective:** This mini review presents current knowledge on hospital radioactive waste, its health hazards, and associated epigenetic effects, with a focus on preventive strategies and public health implications.

**Methods:** Literature from 2000–2025 was reviewed, covering hospital radioactive waste types, health impacts, epigenetic biomarkers, and case studies. Regulatory frameworks and mitigation strategies were also analysed.

**Results:** Hospital radioactive waste includes solid, liquid, and gaseous forms, originating from nuclear medicine, radiotherapy, and research laboratories. Acute exposure can cause radiation sickness, while chronic low-dose exposure is associated with DNA methylation changes, histone modifications, and non-coding RNA dysregulation. Case studies (e.g., Goiânia) underscore gaps in waste management and the potential for human exposure. Emerging biomarkers (e.g., global DNA methylation patterns) allow for early detection of epigenetic alterations. Regulatory adherence and structured waste segregation significantly reduce exposure risks.

**Conclusion:** Hospital radioactive waste is a critical environmental and occupational hazard with long-term epigenetic consequences. Integration of epigenetic monitoring, rigorous waste management, and public health education is essential to mitigate transgenerational health risks. Future research should focus on validating epigenetic biomarkers and establishing standardized hospital-specific waste management protocols

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Renjith S Bhadran,<sup>1</sup> Cherupally Krishnan Krishnan Nair,<sup>2</sup> DM Vasudevan<sup>2</sup>

<sup>1</sup>Department of Public Health, Amrita Institute of Medical Sciences and Research Centre, Amrita School of Medicine, Amrita VishwaVidhyapeetham, India

<sup>2</sup>Department of Health Sciences Research, Amrita Institute of Medical Sciences and Research Centre, Amrita School of Medicine, Amrita VishwaVidhyapeetham, India

**Correspondence:** Cherupally Krishnan Krishnan Nair, Department of Health Sciences Research, Amrita Institute of Medical Sciences and Research Centre, Amrita School of Medicine, Amrita VishwaVidhyapeetham, Kochi-682041, Kerala, India

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## Introduction

### Overview of radioactive waste in healthcare

Radioactive waste in healthcare arises from various medical procedures that involve the use of radioactive materials, such as diagnostic imaging, cancer treatment, and nuclear medicine. These materials include radionuclides which emit radiation as they decay, and are essential for many modern medical technologies. These radionuclides in the radiopharmaceuticals are produced by irradiating a target material in a nuclear reactor or cyclotron, then chemically tagging the resulting radioisotope onto a biologically active drug-molecule. Table 1 gives a list of some of the Radio Isotopes used in Hospitals causing bulk of radioactive waste.

**Table 1** Some of the Radio Isotopes used in Hospitals causing bulk of radioactive waste and their half-lives.

Radio Isotopes		Half Life
Technitium -99m	Tc-99m	6 hrs
Iodine – 131	I -131	8.02 days
Iodine – 125	I -125	59.392 days
Iodine – 123	I -123	13,2 hrs
Flourune – 18	F -18	110 min
Lutitium – 177	Lu-177	6.6 days
Strontium – 90	Sr – 90	28.9 yrs
Tritium H-3	H -3	12.33 yrs
Carbon -14	C -14	5730 yrs

Radio isotope nuclei disintegrate to produce high energy alpha, and beta particles, neutrons and gamma radiation (high energy photons). The Quantity (Activity) of radioactive material is expressed in terms of the Standard international unit (SI) Becquerel (Bq).

These radiations, both particulate (Alpha rays, Beta rays, Neutrons), and photons (gamma radiation) damage cellular DNA by direct energy deposition or by indirect action (creating reactive oxygen species/free radicals, in the cellular milieu or in the proximal environment. The cellular DNA damage can result in gene alterations, cancer etc and hence storage proper disposal of radioactive waste is highly important. Proper storage for 10 half-lives reduces the radioactivity by 1000 fold.

Biological damages due to exposure to different types of radiations particulate and high energy photons, (Gamma rays) differ in the extent due to differences in their tissue damaging (ionization) potential. Based on the biological damage caused, the quantity of radiation exposure is expressed in terms of the unit Sievert (Sv, milliSevert etc). The radiation unit **Gray (Gy)** is used to measure the absorbed dose, particularly in high-dose scenarios like radiotherapy or interventional radiology.

This creates a targeted drug that safely accumulates in specific organs or tumors for precise medical imaging or therapy. The radiations emitted by the radionuclides include high energy radiations (gamma-radiation) or particles such as electrons (beta rays), positrons, alpha particles. These high energy particles and radiations ionize molecules they encounter in their path producing reactive free radicals, and are referred as ionizing radiations. As the cells in the human body contains

more than 80% water molecules aqueous radiolysis inflict damage to the cellular DNA and other biomolecules. Ionizing radiation causes damage to living tissues through a series of molecular events, such as photoelectric, Compton and Auger effects, depending on the radiation energy. Because human tissues contain 80% water, the major radiation damage is due to the aqueous free radicals, generated by the action of radiation on water. The major free radicals resulting from aqueous radiolysis are OH, H,  $e_{aq}^-$ , HO<sub>2</sub>, H<sub>3</sub>O<sup>+</sup>, etc<sup>1-3</sup>). These free radicals react with cellular macromolecules, such as DNA, RNA, proteins, membrane, etc, and cause cell dysfunction and mortality. The DNA damage unless correctly repaired can lead to cellular mortality or mutations and epigenetic alterations. Hence it is important that the handlers of radionuclides and their staff should be well trained in their safe use so that the radiation exposure they receive by handling is minimal, well within permissible limits. The radiation exposure in the area where radionuclides are used or disposed are monitored by survey meters and the personnel exposure is monitored by dosimeters. The dose is usually measured in terms of milliseiverts or seiverts. The permissible dose limit for the radiation workers is **20 mSv per year**, averaged over defined periods of 5 years, with no single year exceeding 50 mSv and for general public it is **1 mSv a year** (higher values are permitted if the average over 5 years is not above 1 mSv a year). The quantity of radionuclides is expressed in terms of milliCuries. Or Curies. The specific activity of the radiopharmaceutical expressed in terms millicuries per mole will indicate the proportion of the radioactive compound.

Some common sources of radioactive waste in hospitals include radiology departments, nuclear medicine facilities (e.g., PET scans, diagnostic radiopharmaceuticals), and radiation therapy used to treat cancers (e.g., cobalt-60, iodine-131, **Technetium-99m** ( $^{99m}\text{Tc}$ )) is the most widely used radiopharmaceutical in the world, accounting for roughly 80% of all diagnostic nuclear medicine procedures globally. It is central to the field of radiopharmacy and medical imaging.

The waste generated can be categorized into solid, liquid, and gaseous forms. Solid waste includes materials such as contaminated gloves, gowns, syringes, and equipment used during procedures involving radioactive substances. Liquid waste, often generated by radiopharmaceuticals used in diagnostics or therapeutic treatments, can also include traces of radioactive isotopes in bodily fluids like urine, which must be handled with care to avoid contamination. Gaseous waste typically comes from the release of radioactive gases used in imaging procedures.<sup>2</sup>

Hospitals and medical institutions must follow stringent regulations to manage these wastes effectively. Inadequate management of radioactive waste can lead to serious public health concerns, including both acute and chronic exposure to radiation. Long-term exposure to radioactive substances, even at low levels, has been linked to increased risks of cancers.<sup>1</sup> Furthermore, radiation exposure can cause environmental contamination, which could result in broader ecological risks, impacting both human and wildlife populations.<sup>3</sup>

### The need for proper disposal and management

The need for proper disposal and management of radioactive waste in healthcare settings is crucial in preventing harmful consequences for public health and the environment.<sup>4</sup> The radioactive materials used in medical treatments and diagnostics pose significant health risks due to their potential to cause cellular damage, mutations, and increased cancer risks, particularly when the radiation exposure is not well controlled. Immediate risks to hospital staff, patients, and surrounding communities can arise from improper storage, handling, or disposal

of radioactive waste.<sup>5</sup> Radiation monitoring instruments are used both for area monitoring and for individual monitoring. The instruments used for measuring radiation levels are referred to as area survey meters and the instruments used for recording the dose equivalents received by individuals are referred to as personal dosimeters.

Proper disposal involves the segregation of radioactive materials based on their radioactive decay rates, handling methods, and potential for contamination. Hospitals must ensure that radioactive waste is securely stored in specially designed facilities or sent to licensed disposal sites that can handle the long-term nature of the materials. Improper disposal, such as throwing radioactive waste into regular waste streams, improper containment, or allowing it to leach into water systems, can lead to long-lasting contamination of the environment.<sup>1</sup> This contamination may persist for decades, making it vital to have rigorous regulatory frameworks in place, such as those proposed by the Environmental Protection Agency (EPA) and the International Atomic Energy Agency (IAEA).<sup>4</sup>

In addition to managing waste within healthcare facilities, the safe transportation of radioactive materials is essential. Stringent protocols must be followed to ensure that radioactive waste is transported securely and without leakage or exposure during transit. This process helps to minimize the risk of accidents or radiation release that could endanger workers, the public, or the environment.<sup>6</sup> Without effective management, the cumulative impact of improperly handled radioactive waste can pose a significant public health burden, particularly in densely populated areas where waste may be more likely to affect broader communities.

Given these risks, there is a strong emphasis on the need for continuous improvements in both the technological and regulatory aspects of radioactive waste management. Advances in waste containment technologies, better training for healthcare workers, and stricter enforcement of international guidelines are necessary to reduce the harmful effects of radioactive waste and ensure that medical radiation practices remain safe and effective for both patients and the public.<sup>7</sup>

## Types of radioactive waste in hospitals

### Medical procedures contributing to radioactive waste

Hospitals produce radioactive waste as a result of various diagnostic and therapeutic procedures that utilize radionuclides. These procedures are essential in modern medicine for diagnosing and treating diseases, particularly cancers. The following are common medical practices that contribute to the generation of radioactive waste in healthcare settings:

**Diagnostic Imaging:** Diagnostic imaging using radioactive materials, known as radiopharmaceuticals, is one of the primary sources of radioactive waste in hospitals. Techniques such as Positron Emission Tomography (PET) scans, Single Photon Emission Computed Tomography (SPECT), and bone scans rely on radiopharmaceuticals to diagnose various medical conditions. For example, radiotracers like technetium-99m and fluorodeoxyglucose (FDG) are used to visualize metabolic processes in the body.<sup>8</sup> After the procedures, the materials used are often discarded as radioactive waste. Some of the radioactive isotopes, like iodine-131 used in thyroid treatments, also produce significant amounts of radioactive waste, including urine and other bodily excretions.<sup>9</sup>

**Cancer treatment:** Radioactive materials are commonly used in cancer therapy, both for external beam radiation and for radioactive implants. For example, iodine-131 is widely used for the treatment

of thyroid cancer. This radioactive isotope is administered to patients, and the waste products from this treatment—such as contaminated bodily fluids—pose significant disposal challenges.<sup>10</sup> Similarly, brachytherapy involves the insertion of radioactive seeds directly into or near a tumor, generating radioactive waste from both the seeds and any associated materials used in the procedure.<sup>11</sup>

**Radiation therapy:** In radiation therapy, high-energy radiation is directed at cancer cells to damage their DNA and stop them from growing. While the radiation used in this form of treatment does not typically generate waste in the form of radioactive substances, the equipment used, such as radioactive cobalt-60 machines, can contribute to radioactive waste. The maintenance of these machines and the disposal of old components like cobalt sources also generates waste.<sup>12</sup>

**Nuclear medicine procedures:** Nuclear medicine procedures, such as the treatment of certain cancers or infection with radiolabeled antibiotics, also generate radioactive waste. The radioactive material used in these therapies may decay and need to be properly disposed of after the treatment is complete.<sup>9</sup>

## Characterization of radioactive waste

Radioactive waste generated in hospitals is classified into different categories based on the physical state of the material, the radiation type emitted, and the specific handling requirements for safe disposal. These categories include solid, liquid, and gaseous waste, each of which poses unique challenges for management and disposal.

### Solid radioactive waste

Solid radioactive waste includes contaminated materials that are used during medical procedures, such as gloves, syringes, gowns, bandages, tissues, and any items that come into direct contact with radioactive substances. This category can also include contaminated equipment, such as imaging devices or tools used in radiation therapy. Solid waste is typically contaminated by low levels of radiation and is considered low-level waste (LLW) in most cases, but certain items, depending on the isotope used, may require more stringent handling protocols. The waste is usually stored in designated containers and often requires secure burial or treatment through specialized incineration processes.<sup>13</sup>

### Liquid radioactive waste

Liquid radioactive waste is a significant concern, as it includes substances such as radiopharmaceuticals and bodily fluids that contain radioactive isotopes. After diagnostic procedures like PET scans or treatments using iodine-131, patients may excrete radioactive materials through urine, sweat, or saliva, all of which must be carefully managed. The liquid waste is typically treated on-site using filtration and decay processes to reduce radioactivity to safe levels before being released into the sewer systems or disposed of via other approved methods.<sup>14</sup> However, improper treatment can result in contamination of water supplies, posing long-term environmental risks.

### Gaseous radioactive waste

Gaseous radioactive waste is often produced during procedures that involve the release of radioactive gases. For example, in the case of imaging techniques like SPECT or certain radiotherapy treatments, radioactive gases may be used or released into the atmosphere. These gases can pose both direct exposure risks to hospital staff and the public, as well as longer-term environmental concerns. Hospitals typically use specialized filtration systems, such as activated carbon

filters, to trap radioactive gases and prevent their release into the environment.<sup>15</sup> However, the handling and disposal of gaseous radioactive waste require careful regulation to avoid contamination.

## Mixed radioactive waste

In some cases, hospital waste can be classified as “mixed waste,” meaning it contains both radioactive and hazardous chemical substances. For instance, contaminated materials like solvents or drugs used in radiopharmaceutical preparation can result in mixed waste. This type of waste requires a complex disposal strategy to ensure both the radiological and chemical hazards are properly managed.<sup>16</sup>

Each type of radioactive waste requires specific treatment and disposal methods, guided by regulations such as those set by the U.S. Environmental Protection Agency (EPA) and the International Atomic Energy Agency (IAEA). Improper handling or disposal of any of these waste categories can lead to serious health risks, environmental contamination, and potential violations of regulatory standards.<sup>17</sup>

## Health hazards from improper disposal

### Immediate risks to healthcare workers and the public

Improper disposal of radioactive waste from hospitals can result in acute health risks, particularly for healthcare workers who handle or come into close proximity to hazardous materials, as well as for the general public if waste is released into the environment. The immediate risks are primarily related to direct exposure to high levels of radiation, either through accidental leaks, improper waste containment, or exposure during waste handling.

### Radiation sickness

One of the most significant immediate health risks is radiation sickness, which occurs when individuals are exposed to high doses of radiation over a short period of time. Symptoms of radiation sickness include nausea, vomiting, fatigue, skin burns, and, in extreme cases, organ failure. Healthcare workers involved in managing radioactive waste, as well as those working in nuclear medicine or radiation therapy departments, are at the greatest risk of accidental exposure. If radioactive waste is improperly stored or disposed of, radiation can leak into the surrounding environment, leading to unintentional exposure. For example, a spill of radioactive material or a breach in a waste container could result in significant exposure for hospital personnel and potentially patients and visitors.<sup>5</sup>

### Radiation burns and skin damage

Radiation burns are a specific type of immediate injury that can occur when someone comes into direct contact with radioactive substances or radiation-emitting materials. These burns are similar to thermal burns but are caused by radiation rather than heat. In a hospital setting, this can happen during procedures where radioactive materials are used, or if waste is improperly disposed of, leading to contamination of surfaces, equipment, or the environment. Healthcare workers handling such waste may be at risk if safety protocols are not followed, such as using protective gear and ensuring proper containment of materials.<sup>17</sup>

### Accidental exposure

The general public can also face risks if radioactive waste is not properly disposed of and accidentally released into the environment. This can happen if radioactive waste is dumped into local water supplies, landfills, or sewer systems. Radioactive particles can spread through air or water, exposing individuals to radiation through

inhalation, ingestion, or skin contact. The immediate impact of such exposure may not be visible initially but can lead to serious health issues if not detected and controlled quickly.<sup>9</sup>

### Long-term health impacts

While the immediate risks of radiation exposure are concerning, improper disposal and mismanagement of radioactive waste can lead to long-term health consequences, particularly for individuals who are exposed to low levels of radiation over extended periods. Chronic health risks arise from cumulative exposure to ionizing radiation, which has the potential to cause severe long-term effects on the human body.

**Cancer:** Prolonged exposure to radiation, even at low levels, is a well-documented risk factor for the development of various types of cancer. Ionizing radiation can damage the DNA within cells, leading to mutations that may result in uncontrollable cell growth and the formation of tumors. Cancer risks associated with radiation exposure include an increased likelihood of leukemia, thyroid cancer, lung cancer, and breast cancer. For healthcare workers who are routinely exposed to low levels of radiation due to improper waste management or inadequate protective measures, this risk is particularly pronounced. Additionally, long-term exposure to contaminated environments—such as residential areas near hospitals where waste has been improperly disposed of—can increase cancer rates in the affected population.<sup>18</sup>

**Genetic mutations:** Ionizing radiation can induce genetic mutations that are passed down to future generations, potentially leading to congenital disabilities, developmental disorders, and inherited diseases. Studies have shown that radiation-induced mutations can affect germline cells, which are responsible for passing genetic material to offspring. When these mutations occur in germline cells, they can be inherited, causing health issues in subsequent generations. This is a particular concern for populations living near areas where radioactive materials are improperly disposed of, or where contamination from hospitals persists.<sup>19</sup> In the case of healthcare workers, occupational exposure can also increase the risk of transmitting genetic mutations, especially if radiation exposure occurs over prolonged periods or at elevated levels, leading to potential epigenetic changes that could be inherited by future generations.

## Epigenetics and radioactive waste exposure

### Understanding epigenetics in the context of radiation exposure

Epigenetics refers to changes in gene expression or cellular phenotype that do not involve alterations to the underlying DNA sequence. These changes can be influenced by various environmental factors, such as diet, stress, chemicals, and radiation. Unlike genetic mutations, which change the DNA itself, epigenetic modifications can impact how genes are turned on or off, without altering the genetic code. Common mechanisms of epigenetic regulation include DNA methylation, histone modification, and non-coding RNA molecules, which can all influence gene activity and cellular functions.

In the context of radiation exposure, environmental factors such as ionizing radiation—often present in hospital settings due to the use of radiopharmaceuticals, radiation therapy, and diagnostic imaging—can induce epigenetic changes. When the body is exposed to ionizing radiation, it can cause molecular damage to cells, leading to epigenetic alterations.<sup>20</sup> These changes can affect gene expression

in ways that may contribute to diseases such as cancer, autoimmune disorders, and neurological diseases. The mechanisms behind these effects are still being explored, but research suggests that radiation-induced epigenetic modifications may have long-lasting implications on health, potentially even passing these changes down to future generations.<sup>21</sup>

For example, ionizing radiation can influence the methylation of certain genes, such as those involved in the DNA repair process. Altered methylation patterns may result in impaired cellular repair mechanisms, increasing the risk of mutations and the development of diseases like cancer. Additionally, histone modifications in response to radiation exposure can affect chromatin structure and gene accessibility, further influencing gene expression and cellular responses to stress.<sup>22</sup>

### Studies linking radiation exposure to epigenetic changes

Several studies have examined the link between radiation exposure and epigenetic changes, with a focus on hospital settings where medical radiation is commonly used. These studies have provided evidence that even low levels of radiation can result in significant epigenetic alterations, potentially leading to adverse health effects.

**DNA methylation and radiation exposure:** One of the most well-studied epigenetic modifications resulting from radiation exposure is DNA methylation. DNA methylation involves the addition of methyl groups to the DNA molecule, typically silencing gene expression. Research has shown that radiation exposure can lead to abnormal methylation patterns in genes involved in cell cycle regulation, apoptosis (programmed cell death), and DNA repair. For example, a study conducted on hospital workers exposed to low doses of radiation found significant changes in the DNA methylation of genes related to tumor suppressors and DNA repair mechanisms. These changes were associated with an increased risk of developing cancer.<sup>23</sup>

**Histone modifications and radiation effects:** Another mechanism of epigenetic regulation impacted by radiation exposure is histone modification. Histones are proteins that help package DNA into a compact structure called chromatin. Chemical modifications to histones can alter how tightly or loosely DNA is packaged, affecting gene accessibility and expression. Research has suggested that radiation exposure can induce modifications to histones, leading to altered gene expression profiles in affected cells. For example, a study involving healthcare workers exposed to radiation found changes in histone acetylation patterns, which were linked to the deregulation of genes involved in stress response and inflammation.<sup>24</sup> These alterations can contribute to long-term health problems, including the development of cancer and cardiovascular diseases.

**Transgenerational epigenetic effects:** One of the most concerning aspects of radiation-induced epigenetic changes is the potential for transgenerational effects. Epigenetic modifications induced by radiation exposure can sometimes be passed down from one generation to the next, even if the genetic sequence remains unchanged. Studies involving animal models and human populations exposed to radiation from medical treatments have suggested that radiation can cause epigenetic changes in germ cells (sperm and eggs), which may be inherited by offspring. This phenomenon has been observed in populations living near nuclear facilities or those exposed to medical radiation. Research on healthcare workers who frequently handle radioactive materials has also suggested a potential for epigenetic changes that could affect future generations.<sup>25</sup>

**Epigenetic effects of low-dose radiation:** While much of the focus has been on high-dose radiation exposure, studies have also suggested that even low-dose radiation—commonly encountered in hospital environments through medical imaging and therapy—can induce epigenetic changes. One study explored the epigenetic impact of exposure to low levels of radiation in radiology departments and nuclear medicine clinics. The findings revealed that healthcare workers exposed to these lower doses exhibited DNA methylation changes, particularly in genes related to tumorigenesis and immune function, suggesting that even minimal exposure could have significant long-term health consequences.<sup>26</sup>

These findings highlight the importance of considering not only the direct genetic damage caused by radiation but also the broader, more subtle epigenetic changes that can affect gene expression. It underscores the need for strict safety measures in medical settings to limit radiation exposure, particularly in hospital workers who are repeatedly exposed to low doses of radiation through medical procedures.

## The role of epigenetics in public health

### Transmission of epigenetic changes across generations

One of the most concerning implications of radiation exposure is the potential for epigenetic changes to be passed down across generations. Unlike genetic mutations, which alter the DNA sequence itself, epigenetic changes involve modifications to the way genes are expressed without changing the genetic code. These modifications can be triggered by environmental factors such as radiation, leading to long-term effects not only in the individual exposed but also in their offspring.

Research has shown that epigenetic modifications can be inherited, meaning that individuals exposed to radiation—whether through medical treatments, occupational hazards, or environmental contamination—could pass down these alterations to their children or even grandchildren. This phenomenon is called transgenerational epigenetic inheritance, and it has raised significant public health concerns, particularly in populations living near areas with high radiation exposure, such as those surrounding nuclear facilities or hospitals that improperly manage radioactive waste.

For example, studies have demonstrated that radiation exposure can alter the DNA methylation patterns in germline cells (eggs and sperm). These changes can affect gene expression in the offspring, potentially leading to an increased risk of developmental disorders, autoimmune diseases, and cancers. Furthermore, transgenerational epigenetic changes may accumulate with each successive generation, leading to a compounding effect on public health. In populations near hospitals or nuclear power plants, there is a growing concern that epigenetic modifications caused by environmental radiation exposure could contribute to a rise in chronic diseases over time.<sup>27</sup> In a hospital setting, where healthcare workers may be repeatedly exposed to low doses of radiation, these transgenerational risks are particularly concerning. Workers' offspring could potentially inherit epigenetic alterations that increase their susceptibility to radiation-induced diseases, amplifying the need for rigorous safety protocols and proper disposal of radioactive materials to minimize such exposure.

### Epigenetic biomarkers for health monitoring

Epigenetic biomarkers hold great promise for early detection and monitoring of health risks associated with radiation exposure,

providing a valuable tool for public health initiatives. These biomarkers can be used to assess the potential risk of diseases related to radiation, such as cancer, cardiovascular diseases, and neurological disorders, by analyzing the epigenetic changes that occur as a result of exposure.

**DNA methylation as a biomarker:** One of the most studied epigenetic modifications, DNA methylation, involves the addition of methyl groups to the DNA molecule, which can silence or activate certain genes. Changes in DNA methylation patterns are often associated with diseases, including those linked to radiation exposure. For example, alterations in the methylation of tumor suppressor genes may increase the likelihood of cancer development. By analyzing the DNA methylation profiles in individuals who have been exposed to radiation, researchers and public health officials could predict the likelihood of disease development in the population. This would help target at-risk groups for early intervention and monitoring.<sup>28</sup>

**Histone modifications and disease prediction:** Histone modifications, which affect how tightly or loosely DNA is packaged within the cell, are another promising class of epigenetic biomarkers. Radiation exposure can induce specific histone modifications, which may be indicative of stress response pathways being activated in the body. Identifying these modifications in biological samples, such as blood or saliva, could serve as a diagnostic tool to assess exposure levels and predict future health risks. For example, in populations living near hospitals or areas with high radiation levels, histone modification profiles could help assess cumulative exposure and identify individuals at risk for conditions like leukemia or lung cancer.<sup>29</sup>

**Non-coding RNAs as biomarkers:** In addition to DNA methylation and histone modifications, non-coding RNAs—molecules that regulate gene expression without coding for proteins—have emerged as important epigenetic biomarkers<sup>30</sup> Specific non-coding RNAs are altered in response to radiation exposure and can be used to track the biological effects of such exposure over time. These small RNA molecules could be used to monitor radiation-induced health risks in individuals who work in healthcare environments or live near radioactive waste sites. Identifying changes in the expression of non-coding RNAs could provide a non-invasive method for early detection of diseases associated with radiation exposure, allowing for more proactive public health management.<sup>31</sup>

**Population-wide screening for epigenetic changes:** In broader public health terms, epigenetic biomarkers could be used in large-scale population screening to assess the prevalence of radiation-induced epigenetic changes in various communities. For instance, a study of healthcare workers, patients, and local residents living near hospitals that deal with radioactive waste could provide insights into the impact of exposure on gene expression across a population. This screening could allow for the early identification of at-risk individuals, who could then be monitored more closely for the development of radiation-related health issues. Moreover, it would help guide policy decisions regarding the safe management of radioactive materials in healthcare settings, further reducing the potential impact on public health.<sup>1</sup>

By integrating epigenetic monitoring into public health strategies, authorities can better understand the long-term effects of radiation exposure on populations and develop more effective preventive measures to mitigate these risks.

## Case studies and real-world examples

### Notable incidents of radioactive waste mismanagement

Improper disposal or mismanagement of radioactive waste has had significant consequences for both public health and the environment. Several high-profile incidents have highlighted the critical need for proper disposal practices and the long-term risks posed by radiation exposure. These case studies underscore the importance of strict regulations and the devastating consequences when those regulations are ignored.

**The Goiânia accident (Brazil, 1987):** One of the most notorious incidents of radioactive waste mishandling occurred in Goiânia, Brazil, in 1987. In this case, an abandoned radiotherapy unit containing cesium-137 was stolen by scavengers from an old hospital building. The thieves opened the container, unaware of the radioactive material inside, and began selling pieces of the equipment to local residents as scrap metal. The cesium-137, a highly radioactive substance, led to widespread contamination. Four people died from radiation exposure, and over 100 others were contaminated, resulting in long-term health consequences. The incident brought global attention to the dangers of improper radioactive waste disposal and the need for more stringent controls over radioactive materials.<sup>5</sup>

**The Sellafield nuclear site (UK, ongoing issues):** The Sellafield site in the United Kingdom has been the subject of numerous incidents involving radioactive waste mismanagement. Although not a hospital, Sellafield is one of the largest nuclear waste facilities in the world, and its operations have faced repeated criticism for poorly managed waste disposal. In particular, liquid radioactive waste was dumped into the Irish Sea for decades, leading to significant environmental contamination. While this case does not directly involve hospital waste, it highlights systemic failures in radioactive waste management that have had lasting public health and environmental impacts. The legacy of these mismanagement practices continues to be felt today, with widespread concerns over radiation levels in surrounding communities.<sup>32</sup>

### Lessons learned and current regulatory measures

The incidents outlined above have led to significant reforms in the management of radioactive materials in healthcare settings and beyond. In response to these high-profile disasters, governments, regulatory agencies, and hospitals have implemented new safety standards and regulations to ensure the proper disposal and management of radioactive waste.

**Stricter regulatory oversight:** Following incidents such as the Goiânia, regulatory bodies like the International Atomic Energy Agency (IAEA) and the U.S. Nuclear Regulatory Commission (NRC) have increased their efforts to ensure that radioactive waste is managed and disposed of safely.<sup>33</sup>

Hospitals and healthcare facilities now face stricter regulations, including detailed tracking of radioactive materials, mandatory reporting of waste disposal practices, and comprehensive training for healthcare workers on handling radioactive substances safely. In some cases, this includes regular safety audits and inspections to ensure compliance with disposal protocols.<sup>1</sup>

**Improvements in waste segregation and containment:** A key lesson from past incidents has been the importance of properly segregating and securely containing radioactive waste at hospitals. Hospitals have adopted more rigorous waste management practices, including the use of sealed containers for radioactive materials, proper labeling, and dedicated waste disposal areas that are off-limits to the public

and non-authorized personnel. Many hospitals now use specialized radioactive waste disposal services, ensuring that hazardous materials are taken to licensed facilities equipped to handle and dispose of radioactive waste safely.<sup>34</sup>

**Public awareness and education:** Another key development has been the increased focus on public awareness regarding the potential dangers of radiation exposure. In many countries, government and public health agencies have taken steps to educate the public and workers about the risks of radiation and the importance of adhering to safety standards. These education initiatives often include training healthcare workers on proper waste handling, as well as educating residents in areas near hospitals and medical facilities on how to identify and avoid radiation hazards.<sup>35</sup>

**Technological innovations in waste disposal:** Advances in technology have played a critical role in improving the safety of radioactive waste disposal. Newer technologies, such as automated systems for the collection and disposal of radioactive materials, have been implemented in healthcare settings.<sup>1</sup> These systems minimize human contact with radioactive materials and ensure that waste is disposed of according to established protocols. Additionally, some hospitals have adopted radiation detection technologies to monitor for accidental leaks or spills of radioactive materials, allowing for rapid intervention and minimizing potential exposure.<sup>36</sup>

**Enhanced international collaboration:** The global nature of radioactive waste management issues has led to increased international collaboration. Countries have come together through organizations like the IAEA to share best practices and develop international standards for managing radioactive waste. These efforts aim to prevent cross-border contamination and improve safety in regions where radioactive materials are used in medical or industrial applications. By learning from past mistakes and working together, countries can develop more effective regulations and systems for waste management.<sup>37</sup>

## Preventive measures and solutions

### Improved waste management systems

A critical element in addressing the public health risks associated with hospital radioactive waste is the implementation of improved waste management systems. Hospitals that use radioactive materials in medical procedures must adopt robust protocols for handling, storing, and disposing of these materials to minimize risks to healthcare workers, patients, and the general public. Effective waste management is essential to ensure that radioactive materials do not leak into the environment, contaminate water supplies, or contribute to radiation exposure over time.

**Segregation and classification of radioactive waste:** One of the key steps in improving waste management systems is to ensure the proper segregation of radioactive waste at the source. Hospital radioactive waste should be carefully categorized into different types, including solid, liquid, and gaseous waste. Each category requires different handling procedures. For instance, solid waste, such as contaminated clothing or equipment, should be placed in clearly labeled, sealed containers that prevent exposure. Liquid waste, such as isotopes used in diagnostic imaging, should be stored in specialized tanks that minimize leakage and ensure proper disposal methods. Gaseous waste, which can arise from specific treatments, should be filtered through air scrubbers designed to remove radioactive particles before being released into the environment.

By implementing these segregation practices, hospitals can reduce the risk of cross-contamination, facilitate the safe handling of

waste, and ensure that materials are disposed of in the most effective manner. Hospitals must also comply with national and international regulations, such as the IAEA's "Safety Standards for Radioactive Waste Management" (2019), which outline detailed procedures for waste handling, storage, and disposal.

**Secure storage and containment:** Proper storage is essential for the safe handling of radioactive waste before final disposal. Storage areas should be equipped with security features to prevent unauthorized access and accidental exposure. Radioactive materials must be stored in specialized facilities with adequate shielding to reduce radiation exposure to personnel and the environment<sup>38</sup> Storage units should be clearly labeled with hazard symbols, and access to these areas should be restricted to trained personnel only.

In the case of long-term storage, hospitals must consider the half-life of the radioactive isotopes being stored. For example, radioactive isotopes with a long half-life, such as cobalt-60 or iodine-131, require secure storage for many years before they decay to safe levels. This requires ongoing monitoring to ensure containment systems are functioning as expected.

**Advanced disposal technologies:** The development of more advanced disposal technologies is key to reducing the environmental impact of radioactive waste. Incineration and deep geological disposal are among the methods that have been proposed for safely eliminating radioactive waste. Incineration involves high-temperature treatment of waste to destroy it, while deep geological disposal involves burying the waste in underground sites that provide natural barriers to radiation leakage. Research and development in these areas can lead to safer, more effective disposal methods that minimize the risk of contamination.

**Recycling and reuse of radioactive materials:** One promising approach to managing radioactive waste is the recycling and reuse of materials.<sup>39</sup> This is particularly relevant for certain isotopes used in medical applications, which can be reprocessed and reused in medical treatments or research. For example, certain nuclear medicines that are no longer in use could be recycled for use in research or reprocessed for disposal in a controlled manner. This would help reduce the volume of radioactive waste generated and decrease the burden on disposal facilities. Hospitals should be encouraged to explore these methods as part of a comprehensive waste management strategy.

## Public health strategies and education

In addition to technological and procedural improvements, public health strategies and education are essential components of managing the risks associated with radioactive waste. It is vital for healthcare workers, hospital administrators, and the general public to be educated about the potential dangers of radioactive waste and the importance of safe disposal practices. Public health campaigns and training programs can help prevent accidents, reduce exposure, and ensure that radioactive materials are disposed of properly.

### Education for healthcare professionals

Healthcare professionals, including doctors, nurses, and radiologists, must be trained to handle radioactive materials safely. This includes understanding the risks associated with radiation, learning how to properly store and dispose of radioactive waste, and being aware of safety protocols to minimize exposure during medical procedures. Training programs should cover topics such as the principles of radiation protection, the safe use of radioactive isotopes in diagnostics and treatments, and emergency response procedures in case of accidents. Hospitals should implement mandatory, ongoing

training for all staff who work with radioactive materials to ensure they remain up-to-date with the latest safety standards and best practices.

Furthermore, healthcare workers should be educated about the potential long-term health effects of radiation exposure, including the increased risk of cancer, genetic mutations, and other radiation-induced diseases. Educating healthcare professionals on the importance of personal protective equipment (PPE) and the use of radiation shielding can also help reduce exposure.

### Public awareness campaigns

Public awareness campaigns are necessary to educate the general population about the potential hazards of living near healthcare facilities that use radioactive materials.<sup>40</sup> These campaigns should focus on how to identify and report possible radiation hazards, what to do in the event of an emergency, and how to protect themselves from accidental exposure. For instance, people living near hospitals should be informed about the potential risks of exposure to radioactive materials, and steps they can take to stay safe. Radiation protection for Nuclear Medicine staff relies on the **ALARA** (As Low As Reasonably Achievable) principle. It is implemented through three core measures—**time**, **distance**, and **shielding**—combined with rigorous personnel monitoring, facility design, and strict regulatory compliance

Furthermore, these campaigns should highlight the importance of community collaboration in the proper disposal of medical waste, stressing the role of both healthcare professionals and the general public in ensuring that radioactive waste is safely handled. Local governments and public health organizations should take the lead in providing resources and organizing outreach programs to inform and engage the community in radiation safety practices.

### Regulatory and policy advocacy

Governments and policymakers have an essential role in promoting public health strategies that prevent radioactive waste mismanagement. Public health campaigns must be supported by stringent policies that ensure hospitals and healthcare facilities comply with safety standards and regulations. Advocacy for clearer guidelines on radioactive waste disposal and the establishment of community monitoring programs can help minimize risks in hospital settings and surrounding communities. Furthermore, public health agencies should collaborate with international bodies like the International Atomic Energy Agency (IAEA) to ensure that healthcare waste management practices align with global best practices.

## Conclusion

### Summing up the health and epigenetic risks

Improper management and disposal of radioactive waste in hospitals present significant public health risks. Health hazards from radiation exposure can manifest in both acute and chronic forms. Immediate risks to healthcare workers and the public include radiation burns, radiation sickness, and contamination. Over time, prolonged exposure to even low levels of radiation can lead to severe health conditions such as cancer, genetic mutations, and reproductive issues.<sup>41</sup> For individuals in proximity to medical facilities handling radioactive materials, the risks can be even more profound if exposure is not properly controlled.

Beyond these direct health impacts, the emerging field of epigenetics has shown that radiation exposure can have far-reaching consequences on gene expression, even without altering the DNA

sequence itself. Epigenetic changes, such as DNA methylation and histone modifications, can affect how genes are turned on or off, influencing the development of diseases long after the exposure has occurred. These alterations may also be passed on to future generations, potentially increasing the burden of radiation-induced diseases on the population.

The potential for widespread and generational impacts of radiation exposure underscores the need for stricter regulatory measures and more effective waste management systems in healthcare settings.<sup>5</sup> Hospitals must ensure that radioactive materials are disposed of safely to prevent contamination of the environment and minimize human exposure to these harmful substances.<sup>42</sup>

## Future research directions

While significant progress has been made in managing radioactive waste, many aspects of its health impacts—especially in relation to epigenetic changes—still remain poorly understood.<sup>43</sup> Future research should focus on several key areas:

### Long-term epigenetic effects of radiation exposure

Research should be conducted to better understand the long-term epigenetic effects of low-dose radiation exposure, particularly in healthcare settings. This includes studying the potential for gene expression changes over multiple generations, as well as investigating the role of epigenetics in the development of radiation-induced cancers and other diseases.<sup>44</sup> Longitudinal studies involving populations exposed to hospital-related radiation would provide critical insights into the lasting impacts of radiation exposure.

### Development of safer waste management technologies

Innovative technologies to improve the safety and efficiency of radioactive waste management should be a key focus of future research. This includes the development of advanced containment systems, more effective disposal techniques such as deep geological disposal, and methods to recycle and reuse radioactive materials in a controlled manner. Technologies that minimize human contact with radioactive waste—such as automated systems for waste handling—could drastically reduce the risks associated with hospital waste.

### Monitoring and biomarkers for radiation exposure

Another important area for future research is the identification of biomarkers that can detect and monitor the long-term effects of radiation exposure.<sup>45</sup> Epigenetic biomarkers could be developed to assess individuals' risk of developing radiation-related diseases, allowing for earlier detection and preventive measures. This research could be pivotal in improving health monitoring strategies for healthcare workers, patients, and communities surrounding hospitals.

### Policy and regulatory development

As the understanding of radiation exposure and its epigenetic effects evolves, there is a need for continuous improvement in the regulatory frameworks governing radioactive waste management.<sup>20</sup> Research on global best practices in hospital waste management, the effectiveness of current safety standards, and the impact of international collaborations could lead to stronger regulations that better protect public health.

### Public health campaigns and community engagement

Further research should also explore the effectiveness of public health campaigns and community-based education programs on

radiation safety. Understanding how to communicate the risks of radioactive waste and engage the public in preventive practices is essential for reducing exposure and increasing compliance with safety standards.<sup>1</sup>

In conclusion, the improper disposal and management of radioactive waste from hospitals pose significant risks to both individual health and public safety. While progress has been made in mitigating these risks, much work remains to be done in understanding the full extent of health and epigenetic consequences. Continued research into the long-term impacts of radiation exposure, the development of safer disposal technologies, and the improvement of public health strategies will be crucial for ensuring that future generations are protected from the harmful effects of radioactive waste.

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## Conflicts of interest

Authors declare that there is no conflicts of interest.

## References

1. Khan S, Syed A, Ahmad R, et al. Radioactive waste management in a hospital. *Int J Health Sci (Qassim)*. 2010;4(1):39-46.
2. Tas A, Ozer AY. Waste disposal and management in radiopharmaceuticals. *FABAD J Pharm Sci*. 2020;45(1):91-103.
3. Cannon G, Kiang JG. A review of the impact on the ecosystem after ionizing irradiation wildlife population. *Int J Radiat Biol*. 2020;98(6):1054-1062.
4. International Atomic Energy Agency. *Disposal of radioactive waste. IAEA safety standards series No. SSR-5: Specific safety requirements*. Vienna, Austria: International Atomic Energy Agency; 2011.
5. Adelodun MO, Anyanwu EC. Public health risks associated with environmental radiation from improper medical waste disposal. *Int J Multidiscip Res Growth Eval*. 2025;6(2):21-32.
6. International Atomic Energy Agency. *Safe Transport of Radioactive Material*. 4th ed. Vienna, Austria: International Atomic Energy Agency; 2006.
7. Sun P, Li G, Zhu Y. Analyzing radiation protection risks in nuclear medicine: Cause investigation and WSR-based countermeasure evaluation. *Risk Manag Healthc Policy*. 2025;18:329-337.
8. Crişan G, Moldovean-Cioroianu NS, Timaru DG, et al. Radiopharmaceuticals for PET and SPECT imaging: A literature review over the last decade. *Int J Mol Sci*. 2022;23(9):5023.
9. Ravichandran R, Binukumar JP, Sreeram R, et al. An overview of radioactive waste disposal procedures of a nuclear medicine department. *J Med Phys*. 2011;36(2):95-99.
10. Palot Manzil FF, Kaur H. Radioactive iodine therapy for thyroid malignancies. In: *StatPearls*. Treasure Island, FL: StatPearls Publishing; 2026.
11. Liu W, McDaniel J, Li X, et al. Brachytherapy using injectable seeds that are self-assembled from genetically encoded polypeptides in situ. *Cancer Res*. 2012;72(22):5956-5965.
12. Ravichandran R. Radioactive cobalt-60 teletherapy machine: Estimates of personnel dose in mock emergency in patient release during source stuck situation. *J Med Phys*. 2017;42(2):96-98.
13. International Atomic Energy Agency. *Classification of radioactive waste. IAEA safety standards series No. GSG-1: General Safety Guide*. Vienna, Austria: International Atomic Energy Agency; 2009.

14. Alfawadi M, Sallah M, Shindakh SH, et al. Assessment of liquid radioactive waste and radiation risks generated from treated patients with isotope I-131 in nuclear medicine units to improve medical waste management. *J Contemp Med Sci.* 2025;11(6):482-489.
15. National Institute for Occupational Safety and Health. *Guidance for filtration and air-cleaning systems to protect building environments from airborne chemical, biological, or radiological attacks.* Cincinnati, OH: Centers for Disease Control and Prevention; 2003.
16. Sreekanth K, Gupta NV, Raghunandan HV, et al. A review on managing pharmaceutical waste in industry. *Int J PharmTech Res.* 2014;6(3):899-907.
17. Iddins CJ, DiCarlo AL, Ervin MD, et al. Cutaneous and local radiation injuries. *J Radiol Prot.* 2022;42(1).
18. Liu X, Su Q, Zhang J, et al. Low-dose radiation exposure and health outcomes among healthcare workers: A multicenter prospective cohort study. *J Health Popul Nutr.* 2025;44(1):414-428.
19. Bouffler SD, Bridges BA, Cooper DN, et al. Assessing radiation-associated mutational risk to the germline: Repetitive DNA sequences as mutational targets and biomarkers. *Radiat Res.* 2006;165(3):249-268.
20. Belli M, Tabocchini MA. Ionizing radiation-induced epigenetic modifications and their relevance to radiation protection. *Int J Mol Sci.* 2020;21(17):5993.
21. Grezenko H, Ekhatov C, Nwabugwu NU, et al. Epigenetics in neurological and psychiatric disorders: A comprehensive review of current understanding and future perspectives. *Cureus.* 2023;15(8):e43960.
22. Song J, Ye L, Ding WQ, et al. How histone modifications influence cellular radiosensitivity: Pharmaceutically targeting epigenetic regulators as a promising avenue to overcome radioresistance. *Acta Pharm Sin B.* 2025;15(12):6093-6140.
23. Mohammed ZM, Lafta FM. The effect of exposure to low-dose ionizing radiation on DNA methylation and relation to genomic stability: A review article. *Int J Health Sci.* 2022;6(S8):4167-4173.
24. Friedl AA, Mazurek B, Seiler DM. Radiation-induced alterations in histone modification patterns and their potential impact on short-term radiation effects. *Front Oncol.* 2012;2:117.
25. Leung CT, Yang Y, Yu KN, et al. Low-dose radiation can cause epigenetic alterations associated with impairments in both male and female reproductive cells. *Front Genet.* 2021;12:710143.
26. Baudin C, Bernier MO, Klovov D, et al. Biomarkers of genotoxicity in medical workers exposed to low-dose ionizing radiation: Systematic review and meta-analyses. *Int J Mol Sci.* 2021;22(14):7504.
27. Heard E, Martienssen RA. Transgenerational epigenetic inheritance: Myths and mechanisms. *Cell.* 2014;157(1):95-109.
28. Ma L, Zhang Y, Xu J, et al. Effects of ionizing radiation on DNA methylation patterns and their potential as biomarkers. *Int J Mol Sci.* 2025;26(7):3342.
29. Kashkinbayev Y, Kazhiyakhmetova B, Altaeva N, et al. Radon exposure and cancer risk: Assessing genetic and protein markers in affected populations. *Biology (Basel).* 2025;14(5):506.
30. Benčik I, Saftić Martinović L, Mladenčić T, et al. From DNA methylation and histone modifications to non-coding RNAs: Evaluating tools for epigenetic research. *Appl Sci.* 2025;15:9940.
31. May JM, Bylicky M, Chopra S, et al. Long and short non-coding RNA and radiation response: A review. *Transl Res.* 2021;233:162-179.
32. International Atomic Energy Agency. *Addressing challenges in managing radioactive waste from past activities. IAEA-TECDOC-2039.* Vienna, Austria: International Atomic Energy Agency; 2024.
33. International Atomic Energy Agency. *The radiological accident in Goiânia.* Vienna, Austria: International Atomic Energy Agency; 1988.
34. Cena RB, Hasi N. Handling of radioactive waste from the use of radionuclides in hospitals. *Int J Comput Exp Sci Eng.* 2024;10(2):207-214.
35. Ganie RO, Saleem MB, Rasheed A. Radiation safety awareness among healthcare workers in education and hospital. *Int J Creat Res Thoughts.* 2025;13(7).
36. International Atomic Energy Agency. *Radiation protection and safety in medical uses of ionizing radiation. IAEA Safety Standards Series: Specific Safety Guide.* Vienna, Austria: International Atomic Energy Agency; 2018.
37. Maalouf A, Agamuthu P. Waste management evolution in the last five decades in developing countries: A review. *Waste Manag Res.* 2023;41(9):1420-1434.
38. International Atomic Energy Agency. *Storage of radioactive waste. IAEA Safety Standards Series No. WS-G-6.1.* Vienna, Austria: International Atomic Energy Agency; 2006.
39. International Atomic Energy Agency. *Radioactive Waste Management Solutions for a Sustainable Future: Proceedings of an International Conference Organized by the International Atomic Energy Agency in Cooperation With the OECD Nuclear Energy Agency, the European Commission and the World Nuclear Association; November 1-5, 2021; Vienna, Austria.* Vienna, Austria: International Atomic Energy Agency; 2023.
40. Berris T, Rehani M. Promoting public awareness and communicating radiation safety. In: *Radiological Safety and Quality.* 2014.
41. Stanford Health Care, Stanford Children's Health, Veterans Affairs Palo Alto Health Care System. *Radiation Protection Guidance for Hospital Staff.* Revised 2023.
42. Allam SME, Algany MMA, Khider YIA, et al. Radiation safety compliance awareness among healthcare workers exposed to ionizing radiation. *BMC Nurs.* 2024;23(1):208.
43. Merrifield M, Kovalchuk O. Epigenetics in radiation biology: A new research frontier. *Front Genet.* 2013;4:40.
44. Bouyahya A, Mechchate H, Oumeslakht L, et al. The role of epigenetic modifications in human cancers and the use of natural compounds as epidrugs: Mechanistic pathways and pharmacodynamic actions. *Biomolecules.* 2022;12(3):367.
45. Rana S, Kumar R, Sultana S, et al. Radiation-induced biomarkers for the detection and assessment of absorbed radiation doses. *J Pharm Bioallied Sci.* 2010;2(3):189-196.