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Radiation Protection in Nuclear Medicine: Principles, Regulations and Contemporary Challenges

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Abstract

Nuclear medicine is now an integral part of healthcare systems across the globe due to innovative diagnosis and therapy through radiopharmaceuticals. The expansion of positron emission tomography/computed tomography (PET/CT), single-photon emission computed tomography (SPECT), and several radionuclide therapies have increased the number of diagnostic interventions that employ ionizing radiation. As a result, the need for radiation protection in nuclear medicine to safeguard the patients, healthcare practitioners, caregivers, and the public has emerged. This review discusses the science of radiation protection in nuclear medicine to justify, optimize, and limit radiation exposure. It also discusses the international policies of the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), and other relevant international bodies. It discusses the impact of rapidly changing imaging technologies, theranostics, occupational radiation exposure, radiation waste, and the protection and safety innovations. This review seeks to describe the innovations and research to enhance nuclear medicine safety in order to sustain the therapeutic value of the technologies.

Keywords: Nuclear Medicine; Radiation Protection; Radiation Safety; Radiopharmaceuticals; Occupational Exposure; Dosimetry; ALARA Principle; Patient Safety.

1. Introduction

Nuclear medicine is an evolving medical specialty that has the hallmarks of cutting-edge healthcare. Compared with other imaging modalities, nuclear medicine permits the visualization of cellular pathology at the molecular and physiological levels (per Cherry et al., 2018). Radiopharmaceuticals enable the detection of cellular pathology that has not yet manifested at the anatomical level, which supports the clinician in optimizing diagnosis and treatment earlier in the disease process.

The combination of positron emission tomography (PET) and computed tomography (CT) or single-photon emission computed tomography (SPECT) and CT, among other hybrid imaging technologies, has improved diagnostic evidence and supported the clinician in the diagnostic process (Bailey et al., 2021). In the field of oncology, PET has unique capabilities for the detection of tumours at diagnosis, and for the purposes of staging, treatment monitoring, and assessing tumour recurrence. Therapeutically, radionuclide therapies with iodine-131, lutetium-177, yttrium-90, and actinium-225 offer new treatment modalities for patients with diverse thyroid, neuroendocrine, prostate, and other malignancies (Hicks et al., 2023).

Radiological medicine has the benefits of advancing clinical practice, yet exposing patients and practitioners to ionizing radiation for diagnostic and therapeutic purposes remains an ethically and scientifically debated concern (IAEA, 2018). Although the radiation doses are low and prescribed, the fears of radiation damage remain the focus of scientific and public discourse (UNSCEAR, 2020).

The biological effects of ionizing radiation are fairly well documented from laboratory, field, and clinical studies. Radiation can damage DNA in multiple ways. High energy radiation does it directly, and it does it indirectly by causing reactive oxygen species (Hall & Giaccia, 2019). The kind of damage done in an exposure event depends on the dose and the exposure context. Some consequences are deterministic effect and tissue responses; others are stochastic effects with tissue responses and a higher general risk of developing cancer. While the clinical cost-benefit ratio adjusts tolerable risk levels for each diagnostic nuclear medicine procedure, keeping exposure as low as reasonably achievable is always an important risk management objective.

Radiation protection is a key component of any nuclear medicine enterprise. The justification, optimization and dose limitation (ICRP, 2021) schemes inform the science and the ethics of communicating that exposure to radiation must be deemed consistent with diagnostic and therapeutic radiation quality and quantity. Realization of these schemes demands the efforts of an extended team, including, but not limited to, physicians, medical physicists, radio pharmacists, technologists, radiation protection officers, and members of the regulatory authority.

The effective implementation of radiation protection programs is especially critical in light of the increasing global demand for nuclear medicine services. It is predicted that within a few years millions of nuclear medicine procedures will be performed annually due to innovations in medicine, the aging population and the increasing prevalence of chronic illnesses (WHO, 2023). Among other things this will lead to new challenges for the protection of workers and the environment, control of radioactive waste and exposure of patients.

The International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) are examples of international organizations that have developed detailed guidance and established regulatory frameworks for the safe use of nuclear medicine (IAEA, 2018; ICRP, 2021). Their documents enable individual countries to develop their own regulations and safety programs.

As the technologies of nuclear medicine continue to develop and the clinical applications become even more varied and sophisticated, understanding the principles of radiation protection is important for healthcare workers and policymakers. The goal of this review is to elaborate the principles of radiation protection and review international standards and regulations and the latest developments in nuclear medicine.

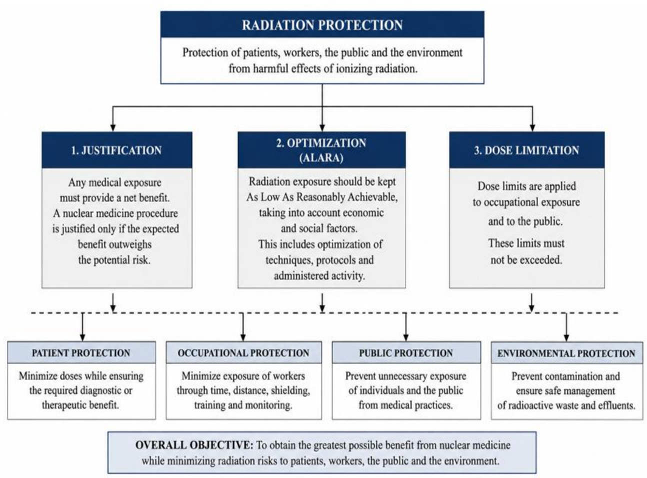

Figure 1. Conceptual Framework of Radiation Protection in Nuclear Medicine

2. Fundamentals of Radiation Protection

Radiation protection is the art and science of minimizing the risks of ionizing radiation to the general population while safeguarding the important uses of radiation within the medical field. It commenced as a specialized field of study and practice utilizing the findings of a number of disciplines, including radiobiology, medical physics, epidemiology, and occupational health. In the field of nuclear medicine, radiation protection includes the provision of safeguard s to the patient as well as the patient’s and medical personnel’s radiation exposure and the provision t o the patient of the best medical service (ICRP, 2021).

An important concept in radiation protection is the knowledge of the biological effects of ionizing radiation. Interaction between radiation and biological tissue occurs when energy is deposited resulting in damage to cellular and molecular structures. Radiation has an affinity to cause damage to the DNA of cells as it is the molecular component containing the genetic code necessary for cellular functioning and for replication. This damage has the potential to cause, amongst others, single and double strand breaks, aberrations at the chromosome level and instability at the genomic level (Hall & Giaccia, 2019). Although biological systems have the capacity to repair many of the lesions caused by radiation damage, some of the lesions may persist and have the potential to cause health effects in the long-term.

The biological effects of radiation are conveniently classified into deterministic and stochastic effects. Deterministic effects only occur when radiation is absorbed above a threshold level. These effects may manifest as tissue damage, cataracts, and skin erythema and radiation-induced necrosis. Stochastic effects, in contrast to deterministic effects, are characterized by an increased risk of developing cancer and radiation-induced genetic effects. The severity of these effects is not influenced by the absorbed dose and there is no threshold level. This classification forms the basis of the rationale on which modern radiation protection is founded (UNSCEAR, 2020). The principle of justification is the first cornerstone of radiation protection.

Any exposure to ionizing radiation must produce a measurable benefit that outweighs the risks in its use (ICRP, 2021). Justification in nuclear medicine means that the diagnostic or therapeutic procedure must be needed to guide the clinical decision for the patient. Physicians must analyse the available diagnostic options along with the potential clinical value before deciding on nuclear medicine therapy. This is vital in sensitive populations, such as pediatrics and obstetrics, due to their greater vulnerability to the effects of radiation.

The second principle is optimization, and the terminology used in the ICRP 2018 as lowest possible means the same as ALARA (As Low As Reasonably Achievable), is used in this context. Optimization means that the maximum level of radiation exposure should be limited to the minimum level required to achieve the desired quality of a diagnostic test or therapeutic procedure. This principle is implemented by proper selection of radiopharmaceuticals including the use of newer technologies and imaging modalities, and incorporated as a part of the quality assurance process. It is also applied in the design of the nuclear medicine facility and the training of the personnel.

Dose limitation is the third principle, and is concerned with managing risk for occupational exposure to ionizing radiation. It is the principle use to manage the exposure of the general population. The limits on occupational exposure is the current scientifically established understanding of health effects of ionizing radiation. It is recommended that the occupational exposure be limited to 20 mSv over five years and to the general public to 1 mSv per year (ICRP, 2021). Although it is ethically and morally justified for a medical procedure to be performed on a patient, the dose to the patient should also be limited to the lowest level possible.

Combining all three of the principles provides a system to balance the benefits versus the risks of exposure to ionizing radiation. Justification, optimization, and dose limitation form the basis for all activities in radiation protection concerning nuclear medicine. As technology develops, providing novel radio diagnostic and radiotherapeutic options, these concepts will be increasingly applicable.

Table 1. Fundamental Principles of Radiation Protection

Principle	**Main Objective**	**Application in Nuclear Medicine**
Justification	Ensure benefits exceed risks	Clinical indication validation
Optimization	Minimize exposure	ALARA implementation
Dose Limitation	Protect workers and public	Regulatory compliance and monitoring

3. International Regulations and Standards

The use of ionizing radiation in medicine necessitates the formulation of evidence-based regulations and the establishment of radiological standards worldwide. A number of organizations have contributed to the formulation of radiation protection standards in the last hundred years. These standards encompass the formulation of safety and protection measures for the patients and professionals in medicine, and the protection of the environment (IAEA, 2018).

The organization that has been the most influential in formulation protection measures is the International Commission on Radiological Protection. The ICRP was formed in 1928, and has been influential in formulating protection measures that have been adopted globally. The principles of justification, optimization and limitation of dose and the protection of those in the workplace, the medical sphere and the environment are the domains of ICRP (ICRP, 2021). ICRP's recommendations are adopted by governments globally.

The standards that are set by the ICRP are made practicable and implementable by the International Atomic Energy Agency (IAEA). The IAEA has adopted the principles of the ICRP and has developed safety standards that cover all spheres, including medicine. The IAEA has developed the International Basic Safety Standards, which set safety standards for the use of ionizing radiation in the medical sciences, industry and research (IAEA, 2018). The IAEA offers member states support to ensure that protective measures are adopted in the medical sphere by safety audits and the provision of equipment and services.

The world health body, the World Health Organization, also protects persons through the provision of safe ionizing radiation in the medicine. The WHO has established programs designed to promote safety, appropriateness, and optimization in radiation and imaging involving patients, as well as in the education of professionals (WHO, 2023). The WHO has called for concerns regarding the risks versus the benefits of diagnostic imaging to be addressed through the application of evidence-based medicine (WHO, 2023).

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) is another important organization in this field. UNSCEAR assesses global patterns of exposure to radiation and evaluates the range of various effects of exposure to radiation on the environment and on health (UNSCEAR, 2020). The reports published by this organization provide the scientific support to the recommendations of the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA).

At the domestic level, it is the regulatory bodies that translate the international recommendations into a legal framework through the establishment of licensing and inspection systems as well as the adoption of enforcement practices. In the context of nuclear medicine, health care organizations are responsible for the development of the radiation protection program in addition to performing exposure monitoring and quality assurance as well as training staff. Regular audits and inspections are performed to assess compliance with established safety standards.

With the advent of new technologies and the rapid growth in the practice of nuclear medicine, the need to unify international and national standards has escalated. Although the methods of regulation may differ from country to country, the focus remains on achieving the greatest utility from the practice of nuclear medicine while minimizing the risks of exposure to radiation. The collaborative efforts of international agencies, regulators, health care providers, and the scientific community is vital to achieving optimal standards of safety in radiation and to the responsible advancement in the practice of nuclear medicine.

4. Radiation Protection for Patients

The protection of patients is a key aspect of safety in nuclear medicine, related to the controlled use of radiation. Unlike exposure in the workplace, radiation used for medical purposes is delivered to achieve a diagnostic or therapeutic advantage. Therefore, the goal is not to avoid exposure to radiation, but to ensure that the benefit of the radiation for the diagnosis or treatment is greater than the risk, and to keep the dose of radiation as low as possible and as appropriate for the purpose of the procedure (International Commission on Radiological Protection [ICRP], 2021).

The protection of patients starts with the justification of a nuclear medicine procedure. Before prescribing a diagnostic nuclear medicine procedure or radionuclide therapy, the healthcare professional is obligated to assess the procedure's necessity, as well as the availability of other imaging techniques, and the procedure's potential usefulness in improving the management of the patient. Exposing a patient to radiation risk with no value to the patient is unethical. Therefore, unnecessary imaging procedures are avoided, and unjustified exposure to radiation is minimized as a result of the implementation of evidence-based referral guidelines (International Atomic Energy Agency [IAEA], 2018).

The reduction of radiation exposure to the patient is also an essential component of the philosophy of protection. The activity of the radiopharmaceuticals administered should be based on the patient's age, body, physical condition, and the reason for the procedure. Because of advancements in imaging technology, substantial reductions in administered activities are possible (Bailey et al., 2021).

Great care must be given to the protection of pediatric patients. Children have increased radiosensitivity when compared to adults and have a longer life span during which radiation-induced effects may occur.

As a result, pediatric nuclear medicine protocols have focused on strategies that lessen the dose and that optimize the protocol for each individual patient. The Image Gently campaign and other similar international efforts have been instrumental in increasing the focus on dose reduction in pediatric imaging and have been advocates for systematically low dose pediatric imaging. (Fahey et al., 2019).

Pregnant and breastfeeding women are also special populations that warrant specific attention. In pregnant women, the exposure of the foetus to radiation is a major consideration in performing any nuclear medicine procedure. In these cases, other imaging procedures that do not use ionizing radiation should be used if possible. If a nuclear medicine procedure needs to be performed, then the dose to the foetus should be as low as possible while still achieving the clinical diagnosis. In breast feeding women, the recommendations of interrupting breast feeding vary with the radiopharmaceutical used and the radiation control measures of the specific radiopharmaceutical (ICRP, 2021).

Education of the patient is an important but often neglected aspect of protection from radiation. When the risks and benefits of a nuclear medicine procedure are clearly explained to a patient, it enhances the patient's ability to make an informed decision and decreases the patient's apprehension about exposure to radiation. An important aspect of radiation therapy is the communication of the potential risks of remaining radioactive to the patient's family and the public (WHO, 2023).

Recent advances in the field of individualized dosimetry also enhance patient protection. The goal of individualized dosimetry is the estimation of risk on an individual basis as opposed to a population based, standardized approach. In particular, this approach is applicable to radionuclide therapy where the absorbed dose can vary greatly between patients. (Flux et al., 2022).

In general, an effective radiation protection strategy for patients relies on a thoughtful integration of clinical justification, dose standardization, innovation in technology, patient education and personalized dosimetry. Continual development of nuclear medicine necessitates patient-oriented radiation protection strategies to preserve and improve safety and efficacy.

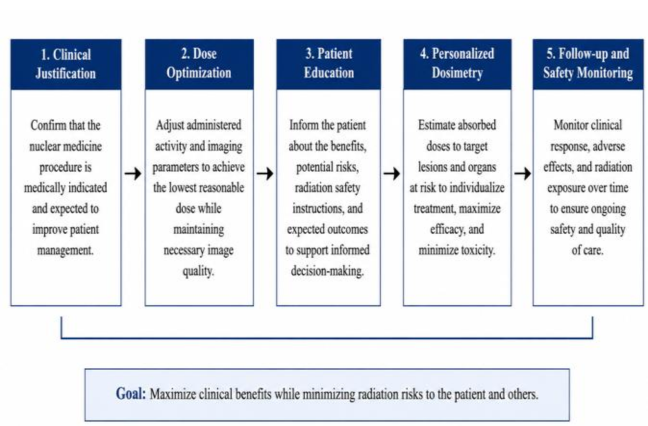

Figure 2. Patient-Centered Radiation Protection Framework

5. Occupational Radiation Protection

Healthcare workers in nuclear medicine are exposed to ionizing radiation at all stages of their job, from preparing and dispensing radiopharmaceuticals to administering them, assisting with imaging, caring for patients, and dealing with radioactive waste. Even though occupational doses are usually within legal limits, the risks of constant exposure over a lifetime of work require that all possible precautions be taken (ICRP, 2021).

The biological rationale for protecting workers from radiation is based on the assumption that the risk of exposure to ionizing radiation is likely to lead to the development of cancer and other forms of stochastic effect. Protection of the workforce from the effect of radiation is an issue of preventing exposure to ionizing radiation in a cumulative way, by the use of various safety measures that have been proven to be reliable and effective. Such measures are within the framework of international recommendations and national legislation, which define limits for radiation doses, requirements for radiation dose control, and the methods of operation (UNSCEAR, 2020).

The classical principles of time, distance, and shielding are the basis of occupational radiation protection. The time principle states that radiation exposure is proportionate to the time spent near a source of radiation. Distance is based on the inverse square law, and shielding is based on the placing of effective barriers, such as lead or tungsten, between the source of radiation and the exposed personnel (Bushberg et al., 2020).

The use of personal dosimeters is an integral part of monitoring programs for occupational radiation exposure. Typical personal dosimeters used by nuclear medicine staff include thermoluminescent and optically stimulated luminescence dosimeters and industrial electronic personal dosimeters. In addition, ring dosimeters are the standard for monitoring extremity doses, as the hands may be subjected to the highest doses of radiation (ICRP, 2021).

Continuous monitoring allows organizations to find high-risk scenarios and take actions to mitigate them (IAEA, 2018). Facility design for nuclear medicine impacts occupational safety and health as well. Ergonomics of the design helps to create separation of controlled areas and the public, reduce unnecessary exposures, and create an unobstructed workflow. Areas such as hot labs, radio pharmacy labs, injection rooms, imaging labs, and waste storage areas are constructed with shielding, layouts for monitoring and ventilation to mitigate occupational exposure and prevent contamination (European Commission, 2021).

Occupational safety has been impacted positively with the advent of automation technology. The use of automated radio pharmacy dispensers, injection, and synthesis systems means less direct manipulatio0n of radioactive materials and thus lower exposure to staff. These systems are widely used in nuclear medicine departments which have a high throughput of PET imaging and therapeutic procedures and radionuclide therapies (Hicks et al., 2023).

Training and education for staff is as important for the protection of occupational radiation safety and health. Staff must understand the physics and biology of radiation, the control of contamination, the effects, and the response to radiological emergencies along with the law. Continuous education allows staff to stay informed regarding radiation safety technology, updated regulatory safety standards, and new safety issues. Studies show that increased training results in reduced staff exposure and increased safety compliance (IAEA, 2018).

Radionuclide therapy raises the concern of extended occupational protection due to the high activity levels associated with the therapy when compared to exposure from diagnostic imaging. Enhanced protection is required for staff preparing and administering therapy radiopharmaceuticals due to the high potential exposure risks. These measures include remote handling systems, specialized shielding devices, contamination monitoring programs, and strict procedural controls (Flux et al., 2022).

An important role in the future of occupational radiation protection will likely be played by digital monitoring, artificial intelligence, and advances in the field of on-line real time dosimetry. These have the potential to assess exposure, improve the management of workflows, and provide an increase in radiation safety performance within the field of nuclear medicine.

Table 2. Major Occupational Radiation Protection Measures

Protective Measure	**Primary Objective**
Time Reduction	Minimize duration of exposure
Distance Maximization	Reduce dose rate
Shielding	Attenuate radiation
Personal Dosimetry	Monitor cumulative exposure
Staff Training	Improve safety awareness
Automation Systems	Reduce direct handling

6. Public and Environmental Protection

Radiation safety programs in nuclear medicine seek to balance the protection of both the public and the environment. While patients are the only group intentionally administered radioactive agents, protections must be instituted to safeguard against excess radiation exposure to the patient’s family, caregivers, visitors, and the populace at large. Similarly, protections must be instituted to ensure that waste radiation does negatively impact the ecosystem (IAEA, 2018).

The public is most commonly exposed to radiation through direct interaction with patients that have undergone nuclear medicine procedures. Of the various imaging modalities, nuclear medicine typically has the lowest dose and therefore lowest risk to the populace. However, radiation therapy using nuclear medicine frequently results in the patient undergoing the procedure becoming a radiation source for an extended time. Therefore, patients undergoing radionuclide therapy are provided detailed instructions on separation during the night and throughout the day from both vulnerable and other members of the therapy staff (ICRP, 2021).

In nuclear medicine, environmental safety is primarily concern with the handling of radioactive waste. This includes everything from contaminated gloves and syringes, to patient excreta and unused radiopharmaceuticals, to contaminated lab supplies. Proper waste handling ensures the materials are removed from the facility and properly disposed of in accordance with the law. The majority of short-lived radionuclides can be safely managed with the decay-in-storage option (European Commission, 2021).

Increased use of radionuclides for therapy has brought an increased focus on the need for environmental protection and monitoring (sustainability).

The proliferation of nuclear medicine requires all global healthcare systems to implement thorough and thoughtful approaches to manage the environmental challenges while delivering optimal care to patients. One of the many ways to manage environmental compliance challenges related to the controlled release of effluents and the dismantling of wastewater and waste disposal systems includes the continuous monitoring of these systems (WHO, 2023).

Trust in nuclear medicine is maintained only if these systems are effective and the professionals are able to manage radiation risks. Engaging with and providing reliable information to the healthcare systems and the community, and with well-defined adjustment strategies, provide the framework for the needed protection of the community and the environment. The field's rapid development makes it essential to integrate sustainable approaches in protective radiation strategies within the environmental protection framework if services in nuclear medicine are to be advanced.

7. Radiation Protection in Radionuclide Therapy

Radionuclide therapy is one of the most innovative and versatile techniques in targeted therapy for both malignant and non-malignant conditions in nuclear medicine. Unlike in diagnosis, where low activity levels are sufficient, radionuclide therapies require the administration of high activities to elicit a therapeutic effect. The increased complexity of radiation protection considerations arises from the high activity levels and the need to protect, in addition to healthcare workers, the patient and the environment (IAEA, 2018).

Radionuclide therapy revolutionizes the treatment paradigm of many conditions. For example, radioiodine therapy with iodine-131 has been the conventional treatment for both thyroid cancer and hyperthyroidism. More recently, therapies utilizing lutetium-177, yttrium-90, radium-223, and actinium-225 have been successful in the treatment of neuroendocrine tumours, metastatic prostate cancer, and therapeutic bone metastases (Hicks et al., 2023). These therapies are intended to deliver ionizing radiation to diseased tissues, thus limiting undesired effects on healthy tissues.

Even with the clinical benefits of radionuclide therapy, effects on radiation protection remain a concern. After therapeutic administration, the patient becomes a source of radiation, and, depending on the administered therapy, family members, caregivers, healthcare workers, and even the general public may become radiation workers. As a result, radiation protection interventions are necessary beyond the clinical setting and, in many cases, beyond the time the patient has been discharged. Regulatory agencies set criteria for the discharge of patients based on the therapeutic activity administered, the measurement of dose rates, and estimated dose to other individuals (ICRP, 2021).

Health physics and radiation protection have become the foundation of modern radionuclide therapy. Traditional cancer therapies used fixed methods because doctors did not know how to control the radiation dose. However, the modern cancer therapy technique, personalized dosimetry, calculates the radiation dose to tumours and sensitive organs. This technique helps reduce the risk of damage to the kidney, bone marrow, liver, and salivary glands (Flux et al., 2022) and helps achieve better results. Personalized dosimetry is an advancement in modern medicine that aligns with precision medicine and evidence-based treatment.

Radionuclide therapy requires advanced radiation safety measures that integrate several safety components/tools (European Commission, 2021). Shielded preparation areas, remote handling devices, automated dispensing systems, and contamination monitoring methods can help achieve safety. Therapy rooms that contain shielding, as well as contamination and safety disposal systems, can help achieve safety for the environment and the therapy workers.

Special radiation safety measures must also be used for the management of radioactive waste in radionuclide therapy. Therapeutic radionuclide therapy patients can excrete radioactive materials in their urine, feces, sweat, and saliva. Therefore, hospitals can no longer allow radioactive materials to exit their waste management systems. Safety measures can include the containment of waste for control periods, special management of waste water, and contamination control as well as meeting the disposal requirements of regulatory bodies (IAEA, 2018).

As the field of personalized theragnostic medicine evolves, radiation safety measures must adapt as new challenges of dosimetry, safety and regulations for therapies that use multiple combination alpha therapies occur. In the future, the role of radiation protection in therapeutic decision making and patient-Centered care will likely become more pronounced.

8. Artificial Intelligence and Future Perspectives

AI is one of the most innovative tools in the healthcare industry and is beginning to make its mark on nuclear medicine. Techniques involving AI may construct offerings such as enhanced diagnostics, improved therapeutic planning, and optimization of radiation protection. Developing and employing AI in nuclear medicine will bring critical advancements in healthcare that are more safe, personalized, and efficient (Hosny et al., 2022).

An exciting aspect of employing AI in the context of radiation protection is dose optimization. AI-based systems may analyse and incorporate the patient's unique characteristics, the imaging protocol, the scanner settings, and the clinical indication to determine the optimal individualized administered activity. Such a proposed system would eliminate unwanted radiation exposure and/or diminish the radiation risk, while still providing a diagnosis of the required imaging study. Numerous studies have demonstrated that the optimization of administered activity using AI improves the quality of diagnostic images (Liu et al., 2023).

AI is revolutionizing dosimetry by simplifying and automating the complex process of calculating absorbed dose. Traditional dosimetry is labour intensive and requires a great deal of mathematical analysis. AI is capable of automating the processes of segmenting organs, defining lesions, and estimating dose, aiding in the consistency and reproducibility of the process, and minimizing the effort. These advancements are critical in the field of radionuclide therapy, as personalized dosimetry is required to achieve the optimal therapeutic dose while still providing a margin of safety (Flux et al., 2022).

Occupational radiation safety may also benefit from the application of AI technology. Intelligent monitoring systems may analyse activities in a work environment to predict situations that may lead to an employee being exposed to unsafe radiation levels. The monitoring system may then provide real-time suggestions to reduce the work-related radiation dose.

The combination of the advances in wearable sensors, digital dosimetry, and predictive analytics will likely allow for the first time the continuous measurement and management of staff exposure and the active management of workplace safety. These advances will likely be the first changes in workplace safety to allow for the transformation of radiation safety programs from a reactive to a predictive and preventive safety program (Harkness et al. 2024).

While optimizing and monitoring radiation doses is one of the primary uses of AI, it can also assist with contamination control and provide better assurance of quality and compliance with safety regulations. The ability of AI and machine learning to identify anomalies in the production of radiopharmaceuticals, identify equipment and safety regulation controls that are failing, and predict the need to perform maintenance will reduce the possibility of personnel and the public being placed at risk of exposure to ionizing radiation.

The introduction of AI, while promising, will provide multiple challenges. Data quality, transparency of the algorithms, and the ethics and safety of the proposed controls will all be challenges to the introduction of AI. The introduction of safety and quality assurance controls in the design of AI and the partnership of these disciplines will help build trust with the AI. Healthcare workers must be trained in the interpretation of AI to better control the safety and quality of healthcare.

In the future, the developing technologies of risk adaptive AI, combined with advanced health measurement technologies and advanced clinical health technologies, are likely to provide individualized health protection within the domain of medical radiation safety, with the potential of improving the safety and quality and providing a greater efficiency in health care.

9. Discussion

The safe and effective application of nuclear medicine hinges upon the protection of radiation, as described in the studies collated in this review. With the expansion of diagnostic and therapeutic applications, the focus and demand of the practices will be the sustainment of radiation safety. The principles of justification, optimization, and dose limitation continue to be the pillars of radiation protection systems and the guidance of modern clinical practice, legislation, and operations world-wide (ICRP, 2021).

The balance of the benefit of the clinical application versus the risk of radiation has been addressed to a large extent with the development of new imaging technologies, radiopharmaceuticals, and individualized dosimetry. However, with continued expansions in the field of nuclear medicine, complex procedures will occupy an increasing focus on the exposure of workers, management of patients, radiation, safety, and the disposal of radioactive waste. These will contribute the need for improvement to the consistent and stable regulatory, educational, and quality assurance frameworks (IAEA, 2018).

Increased integration of diagnostic and therapeutic applications of nuclear medicine has created a significant impetus for protection of radiation with an individualized approach, to prevent the potential therapeutic applications from being hindered by the toxicity of the derived radiation (i.e., theranostics). This is also the case with individualized treatment and the application of therapeutic alpha-emitting radionuclides (i.e., theranostics).

The application of Artificial Intelligence (AI) is an exciting prospect and a huge benefit for future radiation protection. AI technologies, if developed and applied with safety, can affect significant improvement of dose optimization and automation of individual dosimetry with directed advancements to occupational safety and sustainability, as well as an enhancement of informed decision making.

Radiation protection should be viewed from the perspective of a discipline that will impact and sustain the future of nuclear medicine, rather than a regulatory burden. Ongoing partnerships will be vital to solve future problems and to maximize advantages in nuclear medicine and reduce associated risks. Clinicians, medical physicists, radio pharmacists, regulators, researchers, and innovators of technology are all included in the required collaborations.

Conclusion

Radiation protection is vital in nuclear medicine as it safeguards that the advantages surpass the risks concerning ionizing radiation for the patients. The principles of justification, optimization, and limitation provide the core foundation for radiation safety and control the clinical practices worldwide. The ICRP, IAEA, WHO, and UNSCEAR are some organizations that have contributed significantly to the establishment of the scientific and regulatory infrastructure to sustain the safe practice of nuclear medicine.

Continuous advances in molecular imaging, radionuclide therapies, and theranostic applications only increase the pressing need of establishing effective radiation protection systems. Personalized dosimetry, new technological advances in dosimetry and quality assurance systems have shown great promise in addressing some of the newer challenges that radiation safety in nuclear medicine is facing. Integration of AI, advanced dosimetry and digital health offers some of the most exciting opportunities to address radiation safety in nuclear medicine and optimize safety and care for patients undergoing nuclear medicine therapies.

Improving international collaboration and evidenced based regulation, enhancing professional development and education, and supporting innovation in radiation protection will constitute a solid foundation for the development of new methods to solve challenges in radiation protection. Maintaining the high standards of practice in radiation safety will enhance the trust of the community in nuclear medicine and improve patient care.

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