



Exploring Radiation Safety In Medical Imaging: Principles, Safety Protocols, And Risk Management

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Abstract: Ionizing radiation used in medical imaging does not pose significant health risks to medical professionals and patients when proper precautions are taken. Radiation safety programs should be designed to prevent non-stochastic effects and minimize the stochastic effects of ionizing radiation. While ionizing radiation can transfer energy to the materials it interacts with, potentially causing biological effects if used beyond safe limits, these harmful effects are well-documented and supported by research (3). However, awareness of radiation exposure, its effects, and the hazards associated with ionizing radiation, as well as knowledge of radiation safety practices, remains insufficient in the medical field (1,2). The aim of this article is to review the literature on radiation safety measures to be followed in diagnostic radiology.

Key words – Ionizing radiation, radiation dose, effects of radiation, radiation protection, shielding, dose limitation.

I. INTRODUCTION

Ionizing radiation induces damage through direct or indirect mechanisms. The primary target within the cell is deoxyribonucleic acid (DNA). When radiation damages DNA, it can disrupt the genetic code, leading to cell death or mutations. In the direct effect, energy is deposited directly into the DNA molecule, causing damage. In the indirect effect, energy is deposited into surrounding water molecules, generating free radicals that subsequently react with and damage the DNA. The biological effects of radiation depend on several factors, including the type of radiation, whether the exposure is acute or chronic, whether it affects somatic or germ cells, the type of tissue involved, the extent of exposure (whole body or localized), and the individual's sensitivity to radiation.

1.1. Understanding the Biological Impact of Ionizing Radiation

The effects of ionizing radiation can be categorized into deterministic and stochastic effects. Deterministic effects are directly proportional to the absorbed radiation dose, with the severity of these effects increasing as the dose increases. These effects have a threshold value, below which they do not occur. Examples of deterministic effects include lens opacities, skin injuries, infertility, and epilation (4, 1). On the other hand, stochastic effects have no threshold dose for occurrence. While the severity of stochastic effects is not dose-dependent, the probability of their occurrence increases with higher doses. Examples of stochastic effects include cancer and genetic mutations (6).

1.2. Medical Imaging Modalities

The exposure dose to patients varies depending on the medical imaging modality used for scanning. Diagnostic radiology includes various techniques such as fixed radiography, fluoroscopy, mobile radiography, mammography, computed tomography, mobile C-arms, fixed C-arms used in catheter labs and interventional radiology, dual-energy X-ray absorption (DEXA), dental intraoral imaging, and OPG CBCT scanners. Among these, computed tomography and C-arms utilized in interventional radiology are associated with a higher potential radiation dose to patients (6).

1.3. Key Radiation Dose Metrics

KERMA (Kinetic Energy Released per Unit Mass)

KERMA refers to the total initial kinetic energy of all charged particles produced by radiation in a material with a mass of 1 kg. It is measured in Grays (Gy).

Absorbed Dose (D)

The absorbed dose is the amount of energy absorbed per unit mass of the medium at a specific location. It is also measured in Grays (Gy).

Equivalent Dose (HT) and Effective Dose (E)

The equivalent dose is calculated by multiplying the absorbed dose by a radiation weighting factor specific to each type of radiation. The effective dose is derived by further multiplying the equivalent dose by a tissue weighting factor. Both equivalent and effective doses help assess the biological effects of ionizing radiation on tissues and are measured in Sieverts (Sv).

1.4. Principle of Radiation Protection

The International Commission on Radiological Protection (ICRP) and the Journal of Clinical Radiology and Diagnostic Imaging (JCRD) recommend key principles of radiation protection: justification, optimization, and dose limitation (7).

1. **Justification:** While medical imaging offers significant benefits from the use of ionizing radiation, it also carries proven health risks if applied inappropriately. Therefore, every instance of medical exposure involving ionizing radiation must be justified to ensure the safety of the individual.
2. **Optimization:** The effects of ionizing radiation are well understood. In the context of medical exposure, appropriate measures should be taken to minimize radiation exposure for both occupational workers and patients, thereby maximizing benefits while minimizing radiological risks. The principle of optimization in radiological protection is defined as keeping doses "As Low As Reasonably Achievable" (ALARA), taking into account economic and social factors, while remaining below appropriate dose constraints (7).
3. **Dose Limitation:** To prevent harmful effects of radiation on occupational workers, exposure dose limits are established. Different limits apply to the general public and occupational workers. However, there are no specific dose limits for patients undergoing diagnostic or therapeutic examinations. Justification for exposure should come from a specialist clinician, and optimization of radiation protection measures should be applied (7). The recommended dose limits by the International Commission on Radiological Protection (ICRP) are detailed in Table 1.

Type of Dose Limit	Limit on Dose from Occupational Exposure	Limit on Dose from Public Exposure
Effective Dose	20 mSv/yr, averaged over defined five-year periods, with no single year exceeding 50 mSv	1 mSv/yr
Effective Dose	Once employee declares pregnancy, the dose to embryo/fetus should not exceed 1mSv during remainder of pregnancy	-
Equivalent Dose: Lens of the Eye	20 mSv/yr, averaged over defined five-year periods, with no single year exceeding 50 mSv	15 mSv/yr
Equivalent Dose: Skin	500 mSv/yr	50 mSv/yr
Equivalent Dose: Hands and Feet	500 mSv/yr	-

Table No. 1. Dose Limits of Occupational Exposure Recommended by ICRP

1.5. Protection Strategies for Ensuring Radiation Safety in Diagnostic Radiology

Radiation safety is achieved through operational safety and built-in safety measures. **Operational safety** relies on fundamental radiation protection principles and proper work practices (8). **Built-in safety** is established through careful planning during installation and the use of type-approved equipment. Manufacturers must obtain a type approval certificate from the Competent Authority for the commercial production of all X-ray generating medical devices (9).

1.5.1. Operational Safety

In diagnostic radiology, it is essential to adhere to the "As Low As Reasonably Achievable" (ALARA) principle to minimize radiation exposure. By reducing patient radiation exposure, healthcare workers' radiation exposure is also indirectly decreased (10).

Poor image quality can lead to increased radiation doses for patients, while insufficient exposure can result in false-negative diagnoses. Therefore, it is important to deliver an appropriate dose to obtain maximum diagnostic information with the minimum possible radiation exposure. This can be achieved by following the fundamental factors of radiation protection, commonly referred to as the triad: time, distance, and shielding.

1. Reducing the time spent in the exposure room or during fluoroscopy helps minimize radiation exposure for healthcare workers.
2. According to the inverse square law, the radiation exposure dose is inversely proportional to the distance between the X-ray source and the operator. Therefore, maintaining as much distance as possible from the source is crucial to minimize exposure. Doubling the distance from the source reduces the exposure by a factor of four. When using image intensifier fluoroscopy systems and mobile radiography equipment, it is recommended to maintain a minimum distance of 2 meters from the source. This distance results in an exposure dose that is approximately 0.025% of the direct beam intensity (8, 11). The recommended minimum source-to-skin distance for fixed fluoroscopy sources should be no less than 98 cm (15 inches), while for mobile C-arms, it should be at least 30 cm (12 inches) (8, 12). Maximizing the distance from the patient will lead to a lower exposure dose for healthcare workers (13). Additionally, since the patient acts as a source of scatter radiation, primary radiation interacts with patient tissues, resulting in the emission of scatter radiation in multiple directions.
3. The use of shielding materials effectively reduces exposure doses. Shielding can be implemented in the form of personal protective equipment as well as built-in safety measures at the installation site. By placing appropriate materials between the X-ray source and

personnel, radiation exposure is minimized. Radiation protection shielding is utilized in three primary ways: lateral shields, table-hanging curtains, and mobile shields on wheels, as well as ceiling-suspended glass in fluoroscopy. These shields help protect operators and accompanying staff from scatter radiation emitted from the patient's body. Table-hanging detachable lead curtains safeguard the extremities of operators that may not be covered by lead aprons (14). One study involving C-arm procedures demonstrated a significant reduction in radiation exposure to the lower extremities (15). Ceiling-suspended glass reduces scatter radiation exposure to the lenses of the eyes (16, 17). According to AERB recommendations, mobile protective barriers with a lead equivalence of 1.5 mm should be used in radiography and fluoroscopy. Studies have shown that using mobile protective barriers decreases radiation exposure to medical personnel during ERCP procedures (18). Additionally, personal radiation protection equipment, such as lead aprons, thyroid shields, and head shields, helps reduce exposure to scatter radiation. Front shields with a lead thickness of 0.25 mm offer optimal protection from scatter radiation.

In interventional radiology, disposable protective drapes containing bismuth and barium as radiation protection materials can be utilized. These drapes, with a lead equivalence of 0.1 mm, can be positioned on the patient between the operator and the image intensifier, resulting in a reduction of radiation exposure by 14% to 94% (22, 23). During procedures in the interventional radiology suite or fluoroscopy, the hands are often closest to the patient and thus exposed to the primary X-ray beam. To protect the hands, disposable Bi₂O₃-loaded surgical gloves or creams containing Bi₂O₃ are available. However, data on their effectiveness in terms of attenuation and protective capabilities is limited (24).

1.6. Maintenance and Inspection of Radiation Protection Shields

To maintain the integrity of radiation protection shields, they must be stored properly—either hung on storage racks or placed on a flat surface. All radiation protection shields should be inspected biannually to ensure their effectiveness. Each lead apron must be assigned an identification number, and a record should be kept that includes the purchase date, date of quality assurance tests, and the results of those tests. The examination process involves visual inspections, tactile assessments, and X-ray imaging to identify any defects. Fluoroscopic examination should be conducted at a rate of 60-80 kVp.

If a defect in a lead apron exceeds 15 mm² in areas that protect sensitive organs, the apron must be replaced. Additionally, thyroid shields with defects greater than 11 mm² and lead aprons with defects larger than 670 mm² also need to be replaced (25).

1.7. Best Practices for Radiation Safety in Medical Imaging

1. Collimate the area of interest, set the appropriate exposure parameters, and select the correct scanning protocol.
2. Avoid having staff hold the patient; instead, provide protective aprons for personnel assisting with patient positioning.
3. Operate the equipment from behind a protective barrier.
4. Ensure that all built-in safety devices are available and in use during fluoroscopy. Utilize pulsed fluoroscopy, maintain a low frame rate, justify the use of magnification mode, and avoid localized exposure by distributing the exposure dose. During fluoroscopy, stand to the side of the image intensifier.
5. Use personal monitoring devices and radiation protection shields.
6. When using a mobile X-ray unit, stand at least 6 feet away from the patient and wear a lead apron.
7. Cover any critical areas that are not under examination with protective shielding in CT scans.
8. Monitor the Dose Length Product (DLP) in CT and the Dose Area Product (DAP) values in interventional radiology procedures, keeping a record of these measurements. Additionally, provide training for employees working with radiation-generating equipment.

1.8. Mandatory Quality Assurance and Safety Oversight

Periodic quality assurance testing of radiation-generating equipment is mandatory. Records of breakdowns and preventive maintenance should be maintained. Acceptance tests for radiation-generating equipment must be conducted by qualified personnel, including medical physicists. Additionally, a radiation safety officer must be appointed to oversee the implementation of radiation safety measures in diagnostic radiology.

1.9. Radiation Safety Considerations for Pregnant Patients and Children

Medical personnel must screen all women of childbearing age for potential pregnancy before exposing them to radiation. According to the National Commission for Radiation Protection (NCRP), fetal exposure to radiation under 1 rad/rem is considered negligible, while a dose up to 5 rad poses minimal risk compared to other pregnancy risks.

When determining whether pregnancy should be terminated due to radiation exposure, three factors must be considered: gestational age at exposure, estimated fetal dose, patient's preference.

The first trimester is the most sensitive period for fetal development. Malformation risks significantly rise when the fetal dose exceeds 15 rad. For instance, a dose of 25 rad within the first 4 weeks of conception may warrant considering abortion, while 5 rad during the third trimester is rarely a cause for termination. The first two weeks of gestation are critical, often before pregnancy is confirmed. Therefore, imaging is ideally performed within 10 days of the onset of menstruation. According to the Atomic Energy Regulatory Board (AERB), radiation exposure to the abdomen of a pregnant woman should not exceed 2 mSv (5,12).

Children are more vulnerable to radiation due to their higher cell division rate and greater water content, which increases absorption. Radiation doses for pediatric patients should always follow the ALARA principle (As Low As Reasonably Achievable). Reducing radiation-induced damage involves choosing the appropriate imaging technique, adjusting technical settings (e.g., low tube voltage, collimation), and using modern storage-plate systems. For children, additional filtration is required, including 1 mm aluminum and 0.1-0.2 mm copper filters.

Since children often struggle to remain still, fixation devices may be needed to avoid repeat imaging. Pediatric thoracic X-rays use an anterior-posterior (AP) projection to protect the bone marrow in the dorsal part of the body.

Although MRI is a safer alternative to CT, its limited availability, cost, and need for sedation in uncooperative patients often restrict its use. One essential protective measure is the correct positioning of lead shielding to protect sensitive areas like the gonads or eyes.

Finally, reducing repeat imaging is critical. Medical professionals should ensure previous images are available through Picture Archiving and Communication Systems (PACS), which allow integration of prior studies using a unique patient ID. This system helps avoid unnecessary testing and radiation exposure.

Radiation safety in pregnancy and childhood demands strict adherence to best practices, including the use of alternative imaging techniques, precise radiation dosing, and robust safety protocols. Ongoing research into radiation's long-term effects continues to inform guidelines and improve patient care. Public awareness and continued technological advancements are critical to ensuring that these vulnerable groups are protected from the potentially harmful effects of radiation.

II. CONCLUSION

Ionizing radiation poses significant health risks, primarily through DNA damage that can lead to deterministic and stochastic effects. To mitigate these risks in medical imaging, it's essential to adhere to key safety principles, including justification, optimization, and dose limitation. Implementing the ALARA principle and using effective shielding are critical for protecting both patients and healthcare workers.

Special care is required for vulnerable populations, such as pregnant patients and children, necessitating careful planning and appropriate imaging techniques to minimize exposure. Regular quality assurance and inspections of protective equipment further ensure safety. Ongoing research and public awareness are crucial for adapting guidelines and improving patient care while minimizing radiation risks. By prioritizing safety, the healthcare community can effectively balance the benefits and risks of ionizing radiation in medical imaging.

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