Radiation Management in Surgical Imaging.

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***Abstract*— X-ray imaging has become an integral and indispensable component of modern healthcare for both diagnostic and interventional procedures. In orthopedic surgery, the frequent use of image intensifiers such as C-arm fluoroscopy has significantly improved surgical accuracy and outcomes. However, increased dependence on fluoroscopic guidance also raises concerns regarding radiation exposure to patients as well as occupational exposure to surgeons, radiographers, and operating theater personnel. Prolonged or repeated exposure to ionizing radiation can result in potential biological hazards if adequate radiation protection measures are not implemented. The application of radiation safety principles, including justification of procedures, optimization of exposure, and adherence to dose limits, plays a crucial role in minimizing unnecessary radiation while ensuring sufficient image quality for clinical decision-making. Regular inspection and surveillance of protective apparel such as lead aprons, thyroid shields, and protective barriers are essential to maintain their effectiveness and longevity. Radiation safety is a collective responsibility of all operating theater staff and requires proper knowledge, awareness, and strict compliance with safety protocols. Every procedure involving X-ray radiation should be clinically justified, and radiation doses should be kept to the minimum level required to achieve accurate diagnostic and interventional outcomes.**

***Index Terms*— X-ray imaging, C-arm fluoroscopy, Radiation protection, Orthopedic surgery, Occupational radiation exposure**

I. INTRODUCTION

The discovery of X-rays by Wilhelm Conrad Röntgen in 1895 marked a revolutionary advancement in medical science, transforming the diagnosis and management of various diseases. Since then, the application of ionizing radiation has expanded extensively across healthcare, including conventional radiography, computed tomography, nuclear medicine, radiotherapy, and image-guided interventional procedures. These imaging modalities have become indispensable tools in modern clinical practice due to their accuracy, speed, and diagnostic reliability.

With the rapid growth in the number of radiological examinations performed worldwide, concerns regarding radiation exposure have increased. Although most diagnostic procedures involve relatively low radiation doses, repeated exposure may result in cumulative biological effects. Interventional procedures, particularly in orthopedic surgery, frequently rely on fluoroscopic guidance using image intensifiers such as the C-arm. While these techniques enhance surgical precision and reduce operative complications, they also expose patients and operating theater personnel to scattered and direct radiation.

Occupational radiation exposure remains a significant concern for healthcare professionals involved in fluoroscopy-guided procedures. Surgeons, radiographers, nurses, and other operating room staff are at risk of prolonged exposure if appropriate safety measures are not consistently followed. Therefore, adherence to radiation protection principles including justification of procedures, optimization of radiation dose, and limitation of exposure is essential to minimize potential health risks.

The principle of keeping radiation exposure as low as reasonably achievable (ALARA) serves as the foundation of radiation safety practices. Proper use of protective devices, regular monitoring of radiation levels, and adequate training of healthcare personnel are crucial for ensuring a safe working environment. This study aims to emphasize the importance of radiation safety awareness and the implementation of effective protective measures during C-arm–guided

orthopedic procedures to safeguard both patients and healthcare professionals.

II. RADIATION SOURCES AND MEASUREMENT:

Human exposure to ionizing radiation arises from both natural and artificial sources. Natural background radiation, which includes cosmic radiation from outer space and terrestrial sources such as radon gas, contributes a major portion of the total radiation dose received by the population. A smaller but significant contribution comes from man-made sources, predominantly medical imaging procedures, especially diagnostic radiography. In orthopedic practice, occupational radiation exposure to surgeons and healthcare personnel primarily results from scattered radiation emitted from the patient during fluoroscopic procedures rather than from direct exposure to the primary X-ray beam.

Radiation exposure is time-dependent and is commonly expressed as dose per unit time, such as gray per hour (Gy/h) or sievert per hour (Sv/h). The fundamental unit of radiation energy is the electron volt (eV), defined as the energy gained by an electron when accelerated through an electrical potential difference of one volt. Medical X-rays consist of high-energy photons, which are packets of electromagnetic energy.

X-rays and gamma rays differ in their origin but share similar physical properties. Gamma rays originate from the nucleus of radioactive atoms, whereas X-rays are produced when high-speed electrons are decelerated or change direction upon interaction with a target material in a strong electric field. The energy range of diagnostic X-rays typically exceeds 5 keV and commonly lies between 40 keV and 100 keV.

The amount of radiation energy absorbed per unit mass of tissue is measured using the International System of Units (SI) as the gray (Gy), where one gray is equivalent to 100 rad. To assess the biological impact of radiation, equivalent dose and effective dose are used, both expressed in sievert (Sv). Equivalent dose accounts for the type of radiation and its effect on a specific tissue, incorporating radiation-weighting factors. For X-rays, this weighting factor is equal to one. The older unit for equivalent dose is the rem, where 1 Sv equals 100 rem. Effective dose represents the overall risk to the body by considering the sensitivity of different organs using tissue-weighting factors, providing a comprehensive measure of radiation exposure.

III. RADIATION EXPOSURE AND SAFETY:

Radiation exposure during diagnostic and interventional procedures is influenced by the fundamental principles of time, distance, and shielding. These three factors form the basis of radiation protection and play a crucial role in minimizing exposure to both patients and healthcare personnel. International regulatory bodies such as the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) have established guidelines to reduce radiation risks in clinical practice.

Time:Radiation dose is directly proportional to the duration of exposure. Therefore, minimizing exposure time is one of the most effective methods of radiation protection. The use of optimized imaging techniques, such as high kilovoltage (kV) with low milliampere-seconds (mAs), beam collimation, beam filtration, and anti-scatter grids, helps achieve diagnostically adequate images while reducing radiation dose. High-frequency X-ray generators are particularly effective, as they produce higher energy beams that require lower mAs, thereby decreasing patient and occupational exposure. Modern fluoroscopic systems are equipped with audible alarms that alert operators when cumulative exposure time exceeds predefined limits, helping to prevent local radiation injuries. Accurate patient positioning and the use of laser targeting devices further reduce repeat exposures and overall radiation time.

Distance:

Radiation intensity decreases rapidly as the distance from the source increases, following the inverse square law. Doubling the distance from the radiation source reduces exposure to one-fourth of its original value. Regulatory authorities recommend maintaining a minimum distance of approximately 2 meters from the radiation source during image-intensifier fluoroscopy whenever feasible. At this distance, radiation exposure is reduced to a negligible fraction of the primary beam. Additionally, maintaining appropriate source-to-skin

distances is essential to minimize patient dose, with recommended minimum distances for stationary and mobile fluoroscopic units. However, in surgical settings, increased distance must be balanced with procedural accuracy and surgical requirements.

Shielding:

Shielding involves the use of protective barriers to attenuate radiation between the source and exposed individuals. Both personnel and patient shielding are essential components of radiation safety. Commonly used protective devices include lead aprons, thyroid shields, lead goggles, lead gloves, and gonadal shields. Proper use and regular inspection of these protective accessories significantly reduce radiation exposure and enhance occupational safety in fluoroscopy-guided procedures

IV. LEAD APRONS:

Lead is widely used as a protective material in radiation safety due to its high density and high atomic number, which make it highly effective in attenuating ionizing radiation, particularly X-rays and gamma rays. In medical imaging and interventional procedures, lead-based protective equipment serves as a secondary barrier against scattered radiation, which is the primary source of occupational exposure for healthcare personnel. Common protective devices include lead aprons, thyroid collars, gonadal shields, and other shielding accessories.

Standard lead aprons are designed to provide a minimum lead equivalence of 0.5 mm or its structural equivalent using alternative materials such as steel, glass, gypsum, or wood. Aprons with a lead equivalence of 0.5 mm are capable of attenuating nearly all scattered radiation, significantly reducing the radiation dose received by the wearer. Proper coverage is essential for effective protection; therefore, lead aprons should cover the anterior aspect of the body from the neck region to just above the knees, as well as provide adequate lateral coverage from the shoulders to below the hip region.

Lead aprons are available in different designs to suit procedural requirements. Single-piece aprons are lightweight and convenient for short-duration procedures, while two-piece aprons consisting of a vest and skirt provide better weight distribution and are preferred for prolonged interventions. Advances in protective apparel have led to the development of lightweight aprons that incorporate materials such as barium and iodine combined with lead and composite polymers. These aprons offer radiation protection equivalent to conventional lead while reducing overall weight, thereby minimizing strain on the shoulders and spine during extended use.

Thyroid Shield

Although lead aprons are routinely worn during C-arm–assisted orthopedic procedures, the thyroid gland often remains inadequately protected. Neglecting the use of thyroid shields is a significant concern, as the thyroid is highly sensitive to ionizing radiation and prolonged exposure may increase the risk of thyroid disorders, including malignancy. The use of a properly fitted thyroid shield can substantially reduce radiation exposure to the neck region, lowering the effective dose by several times and significantly decreasing overall occupational exposure. Consistent use of thyroid shielding is therefore strongly recommended as an essential component of radiation safety practice.

V. STORAGE OF LEAD APPARELS:

Proper care and storage of lead protective apparel are essential to maintain their structural integrity and radiation-shielding effectiveness. Lead-based protective devices are susceptible to damage if handled or stored incorrectly. Repeated folding, dropping, stacking, or improper placement can cause internal fractures, cracks, or thinning of the lead layer, which may compromise the protective capability of the apparel without being externally visible.

To ensure optimal performance and longevity, lead aprons and associated protective equipment should be stored in a manner that prevents mechanical stress and deformation. Protective apparels such as lead aprons, thyroid collars, side shields, and lead gloves should be stored either flat on designated surfaces or hung on specially designed hangers and racks that provide uniform support. Hanging aprons on inappropriate supports, such as narrow hooks or chairs, should be avoided as this may lead to creasing and internal damage.

Regular inspection of lead protective apparel is recommended to detect early signs of wear, tears, or internal defects. Proper storage practices combined with routine quality checks help preserve the shielding effectiveness of lead apparel and ensure continued

radiation protection for healthcare personnel involved in fluoroscopy-guided procedures.

VI. STANDARDIZATION, TESTING, AND REJECTION PROCEDURE OF LEAD APPARELS:

To ensure effective radiation protection, all lead protective apparels should undergo proper standardization and quality control procedures from the time of procurement. Each lead apron and radiation protection accessory should be assigned a unique identification number and labeled with the date of purchase and date of initial use. Maintaining detailed records is essential and should include information such as identification number, lead equivalence, manufacturer details, inspection dates, and results of periodic testing.

Routine quality assurance testing is necessary to verify the continued effectiveness of lead protective apparel. Annual inspection should include thorough visual examination and tactile assessment to identify visible defects such as surface cracks, tears, perforations, thinning of material, or damage to fastening components like Velcro straps and buckles. Since most lead aprons are encased in a non-protective outer covering, visual inspection alone may not reveal defects in the internal lead layer.

Therefore, fluoroscopic evaluation is recommended as a standard method for detecting hidden defects within the protective material. This examination should be performed using manual exposure settings, typically in the range of 60–80 kVp, to clearly visualize variations in shielding. Areas of compromised lead appear as bright or lighter regions on fluoroscopic imaging, whereas intact shielding appears darker. Protective apparel exhibiting significant defects or loss of lead integrity should be withdrawn from clinical use and appropriately discarded or replaced.

Implementation of systematic testing and rejection protocols ensures continued radiation protection, enhances occupational safety, and supports compliance with established radiation safety standards.

Rejection Criteria:

Lead protective apparel has a limited-service life, generally averaging around five years, although defects may develop earlier depending on the frequency of use, handling practices, and storage conditions. Due to the high cost of lead aprons and associated protective devices, clear rejection criteria are essential to balance safety and cost-effectiveness. Lead aprons should be considered for replacement if defects exceed acceptable limits, particularly in regions that protect radiosensitive organs.

Protective apparel covering critical areas such as the chest and abdomen should be rejected if defects exceed approximately 15 mm^2. Thyroid shields, due to the high radiosensitivity of the thyroid gland, require stricter standards and should be replaced if defects larger than approximately 11 mm^2 are detected. Defects located in non-critical regions of the lead apron, such as the posterior surface or along seams, may be tolerated up to larger dimensions; however, defects exceedingly approximately 670 mm^2 in these areas necessitate replacement. Aprons that do not meet the rejection criteria may continue to be used, provided that the defect size and location are documented. Regular inspections, preferably conducted biannually, are recommended to monitor the progression of defects and ensure continued protective efficacy.

VII. RADIATION PROTECTION SURVEY AND PROGRAMME:

A comprehensive radiation protection program is essential for maintaining safety standards in healthcare facilities that utilize ionizing radiation. Every hospital should establish a structured radiation protection program overseen by a Radiation Safety Committee (RSC) and a designated Radiation Safety Officer (RSO). This program ensures compliance with national and international radiation safety guidelines and promotes a culture of safety among healthcare professionals.

The Radiation Safety Committee should be multidisciplinary in composition, typically including a radiologist, a medical physicist, a nuclear medicine specialist, a senior nursing representative, and a clinician experienced in radiation-based procedures. The primary responsibilities of the RSC include conducting periodic radiation protection surveys, evaluating occupational exposure levels, reviewing safety protocols, and ensuring proper training of staff. Regular monitoring and assessment of radiation safety practices help identify potential hazards and facilitate timely implementation of corrective measures, thereby

reducing radiation-related risks to patients and healthcare personnel.

VIII. MONITORING OF RADIATION EXPOSURE AND SAFETY LIMITS:

Monitoring radiation exposure is a critical component of radiation safety, as it helps assess the dose received by patients and healthcare personnel and ensures compliance with recommended safety limits. Regular dose monitoring allows timely identification of excessive exposure and facilitates the implementation of corrective measures.

IX. MEASUREMENT OF PATIENT DOSE

Patient radiation exposure is commonly assessed by measuring the entrance skin dose using dosimeters placed within the field of exposure. This method provides an estimate of the radiation dose received at the skin surface during diagnostic or interventional procedures. For example, a routine chest radiograph typically results in a low entrance skin dose, while exposure to sensitive organs such as the gonads remains minimal. In fluoroscopy-guided procedures, patient dose may vary depending on exposure time, imaging technique, and equipment settings.

Documenting the radiation dose received by the patient after each fluoroscopic procedure is considered a good clinical practice. Including dose information in the radiological report promotes transparency, increases patient awareness regarding radiation safety, and assists clinicians in evaluating cumulative exposure during future imaging investigations.

Personnel Dosimetry

Personnel dosimeters are used to measure occupational radiation exposure received by healthcare workers over a defined monitoring period, usually three months. These devices provide an accurate record of cumulative radiation dose and help ensure that exposure remains within permissible limits.

Two commonly used types of personnel dosimeters are film badge dosimeters and thermoluminescent dosimeters (TLDs). Film badge dosimeters utilize radiation-sensitive films placed between filters to detect and estimate radiation exposure. Thermoluminescent dosimeters operate on the principle that certain crystalline materials, such as lithium fluoride and calcium sulfate, emit light when heated after radiation exposure. The intensity of the emitted light is directly proportional to the absorbed radiation dose.

For optimal monitoring, it is recommended that two dosimeters be worn by personnel involved in fluoroscopy-guided procedures. One dosimeter should be worn at the collar level outside the lead apron to measure exposure to unprotected areas such as the head and neck, while the second dosimeter should be worn beneath the lead apron at trunk level to estimate dose to protected regions. If only one dosimeter is available, it should be worn at the collar outside the lead apron, as the neck region typically receives significantly higher radiation exposure compared to the shielded trunk.

X. RADIATION PROTECTION TO SURGEON AND SURGICAL TEAM

With the increasing reliance on fluoroscopy in modern orthopedic surgery, particularly due to the adoption of minimally invasive and percutaneous techniques, radiation protection for surgeons and the operating room team has become a critical safety concern. Prolonged and repeated exposure to scattered ionizing radiation places surgeons, assistants, radiographers, and nursing staff at risk, making strict adherence to radiation safety practices essential.

Protective apparel plays a fundamental role in reducing occupational radiation exposure. It is recommended that all personnel working in the fluoroscopic field wear lead aprons with a minimum lead equivalence of 0.5 mm. Given the high radiosensitivity of the thyroid gland, thyroid shields should be worn consistently during all fluoroscopy-guided procedures. When leaded eyewear is used, care should be taken to orient the head appropriately to minimize lateral exposure. Direct exposure of hands to the primary X-ray beam should be avoided whenever possible, as it significantly increases radiation dose. In situations where hand exposure is unavoidable, the use of leaded gloves or radiation-attenuating hand protection may provide additional safety. Pregnant surgical personnel should avoid direct involvement in fluoroscopy-assisted positioning or handling of imaging equipment.

Optimization of fluoroscopy technique further contributes to dose reduction. Proper beam collimation limits the exposed area, reducing scatter radiation despite increasing localized skin dose. Most modern C-arm systems are equipped with automatic brightness control (ABC), which adjusts tube voltage and current to maintain image quality; using this mode is recommended to avoid unnecessary exposure. Surgeon-controlled fluoroscopy and automatic image optimization can significantly decrease fluoroscopy time. Additionally, low-dose or pulsed fluoroscopy modes should be preferred over continuous exposure, as they provide adequate image quality while substantially lowering radiation dose.

Whenever feasible, alternative imaging technologies should be considered. Mini C-arm fluoroscopy units can be used for extremity procedures and deliver lower radiation doses compared to standard C-arm systems. Laser targeting grids assist in accurate positioning and reduce repeat imaging. Digital zooming on the monitor should be favored over magnification at the C-arm, as the latter markedly increases radiation exposure. The use of mobile or ceiling-mounted lead shields provides additional protection to both surgical staff and patients.

Proper positioning of the fluoroscopy unit is another key factor in radiation safety. The X-ray tube should be placed as far as possible from the surgeon and operating staff, with personnel positioned on the image intensifier side rather than the generator side to minimize scatter exposure. Orienting the X-ray beam from below upward further reduces scatter radiation. Maintaining a minimum distance of approximately 36 inches from the radiation beam can result in a substantial reduction in effective dose. Regular calibration and maintenance of fluoroscopic equipment ensure optimal performance at the lowest effective radiation dose.

Advanced imaging and navigation technologies have also demonstrated significant benefits in reducing radiation exposure. Computer-assisted surgery systems utilize pre-acquired digital images to guide surgical navigation, thereby minimizing the need for repeated fluoroscopic imaging. Studies have shown reduced fluoroscopy time during spine and pedicle screw instrumentation procedures when navigation systems are employed. Similarly, O-arm imaging systems provide real-time three-dimensional and multiplanar imaging, allowing surgical staff to exit the room or remain behind shielding during image acquisition, eliminating the need for continuous lead apron use. G-arm imaging systems enable simultaneous biplanar imaging, improving accuracy while reducing overall procedure time and radiation exposure.

In addition to technological advancements, educational initiatives play an important role in radiation safety. Programs such as Image Wisely for adults and Image Gently for pediatric patients emphasize responsible imaging practices and aim to minimize unnecessary radiation exposure through awareness and optimized imaging protocols. Collectively, these strategies contribute to a comprehensive approach to radiation protection for surgeons and the surgical team.

XI. RADIATION PROTECTION TO PATIENT

Ensuring radiation safety for patients is a fundamental aspect of fluoroscopy-guided diagnostic and interventional procedures. Particular attention must be given to protecting radiosensitive organs, especially in children and young adults, as they are more vulnerable to the long-term effects of ionizing radiation. Organs such as the thyroid gland, breast tissue, and gonads require special consideration during imaging procedures involving X-ray exposure.

Protective shielding should be used whenever feasible to minimize patient radiation dose. Lead aprons or gonadal shields should be appropriately positioned to protect reproductive organs from direct exposure to the primary X-ray beam. Additionally, lead collars or shields may be used to protect the neck and upper thoracic region, thereby reducing radiation exposure to the thyroid and breast tissue. The effectiveness of shielding depends largely on correct placement relative to the direction of the X-ray beam.

Shield placement must be carefully planned based on the orientation of the X-ray tube during the procedure. Improper positioning of lead shields, particularly placing them over radiosensitive organs without considering beam direction, may be ineffective and, in some cases, may increase radiation exposure due to scatter. Therefore, shielding should be applied before patient preparation and surgical draping, ensuring optimal coverage without interfering with imaging or procedural requirements.

Patient positioning also plays a crucial role in radiation protection. During fluoroscopic examinations, patients should be positioned as close as possible to the image intensifier and as far as possible from the X-ray tube. This configuration reduces the amount of scattered radiation and lowers the overall radiation dose received by the patient. Adhering to these protective strategies helps minimize radiation risks while maintaining the diagnostic and procedural benefits of fluoroscopic imaging.

XII. PREGNANT PATIENTS:

Radiation protection in pregnant and potentially pregnant patients requires special consideration due to the sensitivity of the developing fetus to ionizing radiation. It is the responsibility of medical personnel to routinely screen women of reproductive age for possible pregnancy prior to radiological procedures. Fetal radiation doses below 1 rad (10 mGy) are generally considered to carry negligible risk, and national radiation safety guidelines indicate that fetal exposure up to 5 rad poses minimal risk when compared with other naturally occurring pregnancy-related hazards.

The decision regarding pregnancy continuation following radiation exposure depends on several critical factors, including the gestational age at the time of exposure, the estimated fetal radiation dose, and the informed wishes of the patient. The first trimester, particularly the period of organogenesis, represents the most sensitive phase for radiation-induced developmental effects. The risk of congenital malformations increases significantly when fetal exposure exceeds higher dose thresholds. Early gestational exposure carries greater concern, whereas similar exposure levels during the later stages of pregnancy are far less likely to justify pregnancy termination.

To minimize inadvertent fetal exposure, radiological examinations in women of childbearing age are ideally performed during the early post-menstrual phase. In established pregnancy, regulatory authorities recommend strict dose limits, and the radiation exposure at the surface of the abdomen should remain well within prescribed safety levels. Whenever possible, alternative imaging modalities that do not involve ionizing radiation should be considered.

Children:

Children are more susceptible to the harmful effects of ionizing radiation compared to adults due to higher cellular division rates and longer post-exposure life expectancy. Their tissues also contain higher water content, which increases radiation absorption. Consequently, radiation protection strategies in pediatric imaging must be rigorously implemented.

All pediatric radiological examinations should adhere strictly to the ALARA (As Low as Reasonably Achievable) principle. Radiation dose optimization can be achieved through appropriate selection of imaging techniques, use of low tube voltage, effective beam collimation, minimal exposure time, and modern digital imaging systems. Additional filtration is recommended for pediatric imaging to further reduce unnecessary radiation exposure. Immobilization techniques may be employed to minimize motion artifacts and prevent repeat exposures.

Imaging protocols for children differ from those used in adults. For example, thoracic imaging in infants and young children is typically performed using an anteroposterior projection due to the distribution of active bone marrow. Although advanced imaging modalities such as magnetic resonance imaging can replace computed tomography in certain cases, limitations such as availability, cost, scan duration, and the need for sedation restrict their routine use.

Simple protective measures, including correct placement of lead shielding over radiosensitive organs such as the gonads and eyes, remain highly effective. Additionally, unnecessary repeat imaging should be avoided by ensuring proper access to previous investigations. Picture Archiving and Communication Systems (PACS) facilitate secure storage, retrieval, and integration of imaging studies, enabling clinicians to review prior examinations and reduce redundant radiation exposure. Treating physicians bear a crucial responsibility in ensuring judicious use of radiological investigations, particularly in vulnerable populations such as pregnant women and children

XIII. SUMMARY:

Radiation protection is an integral component of hospital setup. The principles of radiation protection are to provide protection from undue exposure of radiation to medical personnel and patient. Radiation protection program should include justification of the

procedure involving the radiation exposure, use of minimum radiation exposure just adequate for diagnostic and interventional procedures. Regular surveillance of radiation exposure, protection and educational activities should be the part of responsibilities of RSO and other administrative authorities of the hospital.

Orthopaedic surgeons are relying more heavily on X-rays, CT scans, and fluoroscopy duringadvanced procedures. For this reason, we must be well versed in the safety concerns of allforms of ionizing radiation. Many measures exist to protect the patient, surgeon, and medical personnel from the harmful effects of radiation. Each situation involving X-ray radiation should be carefully evaluated to limit adverse effects, and ICRP guidelines should be followed to prevent potential harm to healthcare providers and patients.

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