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Review Article

Radiation safety in orthopaedic surgery: educational guidelines for surgeons using X-rays and C-arm fluoroscopy

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ABSTRACT

Orthopaedic surgeries frequently rely on intraoperative imaging, particularly X-rays and C-arm fluoroscopy, to enhance procedural accuracy. However, these modalities expose surgeons and operating theatre personnel to ionizing radiation, leading to both immediate and long-term health risks. Despite the availability of protective measures and the ALARA (As low as reasonably achievable) principle, adherence to radiation safety in orthopaedics remains suboptimal. This review highlights radiation hazards in orthopaedic practice and presents practical, evidence-based strategies for minimizing occupational risk. A comprehensive literature review was performed, focusing on intraoperative radiation exposure in orthopaedics, its biological effects, and preventive measures. International radiological safety guidelines, surgical protocols, and recent orthopaedic studies were analyzed, with emphasis on practical recommendations for operative settings. Ionizing radiation can cause deterministic effects (cataracts, skin injury) and stochastic effects (malignancy, infertility, genetic mutation). Key strategies to reduce exposure include minimizing fluoroscopy time, increasing distance from the source, using shielding devices, adopting pulsed fluoroscopy, and optimizing C-arm positioning. Pregnant staff require additional precautions such as double dosimetry and modified work schedules. Despite the availability of personal protective equipment (PPE), lack of structured education and poor compliance remain major challenges. Radiation exposure during orthopaedic procedures is a preventable occupational hazard. Strict enforcement of safety protocols, adequate PPE, routine training, and institutional monitoring are essential to protect surgeons and operating teams.

Keywords: Radiation safety, C-arm fluoroscopy, Orthopaedic surgery, Radiation protection, ALARA principle

INTRODUCTION

Orthopaedic procedures increasingly rely on intraoperative imaging, especially with the widespread use of C-arm fluoroscopy and digital X-rays.[1] While these tools have revolutionized surgical precision and minimally invasive techniques, they bring with them a significant yet often underappreciated occupational hazard-radiation exposure. Studies show that a substantial number of orthopaedic surgeons lack adequate knowledge about radiation safety protocols, equipment usage, and long-term risks.[2]

The hidden danger of cumulative radiation exposure can result in malignancies, cataracts, thyroid dysfunction, infertility, and other tissue damage. More so, operating theatre staff and residents-often closer to the radiation source-are equally vulnerable.[3] Despite the well-known ALARA principle, the actual implementation of safety guidelines remains inconsistent.

This article aims to serve as a comprehensive educational guideline for orthopaedic surgeons, trainees, and operation theatre staff. It outlines the risks associated with radiation exposure, practical methods for reducing dose, and the

necessary protocols to safeguard both patients and healthcare professionals.

This lack of awareness directly impacts compliance with safety measures and underlines the necessity of structured institutional protocols and routine refresher training.

BIOLOGICAL EFFECTS OF RADIATION

Exposure to ionizing radiation during orthopaedic procedures can have both deterministic (dose-dependent) and stochastic (probability-based) effects on human tissues. The most vulnerable tissues include rapidly dividing cells, such as those in the skin, thyroid, gonads, lens of the eye, and bone marrow.[4,5]

Common health risks from occupational radiation exposure include carcinogenesis, with increased risk of cancers such as thyroid, breast, colon, prostate, and skin cancers.[4] Skin damage, including erythema, epilation, and dermatitis, may occur with prolonged exposure. The risk of radiation-induced cataracts increases with cumulative lens exposure, while long-term exposure may also affect fertility, particularly in younger surgeons. Genetic damage remains a concern, potentially contributing to mutations affecting future generations.[5]

The international commission on radiological protection (ICRP) recommends an annual occupational exposure limit of 20 mSv averaged over 5 years, with no single year exceeding 50 mSv. Pregnant healthcare workers are advised to limit fetal exposure to less than 1 mSv throughout pregnancy, with special attention during the first trimester.[6]

Radiation intensity decreases significantly with increasing distance, as described by the inverse square law. At 1 meter, exposure is approximately 0.1% of the original, and at 2 meters, it drops further to 0.025%. This highlights the importance of maintaining adequate distance from the radiation source whenever possible.[7]

These biological effects emphasize the necessity of strict adherence to radiation safety principles in daily orthopaedic practice.[7]

PRINCIPLES OF RADIATION PROTECTION

Radiation protection in orthopaedic surgery is centered around the internationally recognized ALARA principle. This concept guides exposure reduction through three main strategies: time, distance, and shielding.[8]

Time

Fluoroscopy duration should be minimized to reduce cumulative exposure. Surgeons must use fluoroscopy only when essential and avoid unnecessary imaging. The number of image acquisitions can be reduced through proper planning and hand-eye coordination. Recording exposure time during each procedure is also valuable for audit and training purposes.[8]

Distance

Radiation exposure decreases with increasing distance. Doubling the distance reduces exposure to one-fourth, making it essential for operating personnel to maintain a minimum of one meter from the X-ray tube whenever possible. Surgeons not directly involved in imaging should step back or move behind a protective barrier.[7]

Shielding

Proper use of shielding devices significantly reduces radiation exposure. Lead aprons (0.5 mm Pb) can reduce exposure by up to 99%, while thyroid shields and leaded glasses protect the thyroid gland and lens of the eye, respectively. Lead gloves provide hand protection during close procedures, and mobile lead screens may be used for shielding non-scrubbed staff. These protective devices must be worn correctly and inspected regularly for cracks or defects.[9,10]

These three pillars of radiation protection-time, distance, and shielding-are simple yet often underutilized. Their consistent application can significantly mitigate occupational risk without compromising surgical workflow.[8]

C-ARM USAGE PROTOCOLS

C-arm fluoroscopy unit is indispensable in modern orthopaedic surgery, particularly for trauma, spine, and minimally invasive procedures. However, improper usage can significantly increase radiation exposure for both patients and operating personnel. Optimal positioning and technical principles are essential to minimize this risk. Correct positioning of C-arm is crucial-placing X-ray tube below operating table with image intensifier above patient reduces scatter radiation directed toward surgical team. In contrast, placing X-ray source above patient increases scatter toward surgeon's head and torso. Additionally, keeping image intensifier as close to patient as possible reduces beam spread and improves image quality.[1]

Fluoroscopy technique selection further impacts exposure. Pulsed fluoroscopy emits X-rays in short bursts rather than continuously and has been shown to reduce radiation dose by up to 64% without compromising image quality in most orthopaedic procedures.[11] Continuous fluoroscopy, while providing a steady image stream, results in much higher cumulative exposure and should be avoided unless absolutely necessary. Beam collimation is another critical principle, as limiting the X-ray field to only area of interest reduces scattered radiation and enhances image contrast. Large field imaging, particularly of long bones/spine, should be avoided unless required. Oblique projections and steep angulations should also be minimized, as they increase scatter radiation exposure.[8,11]

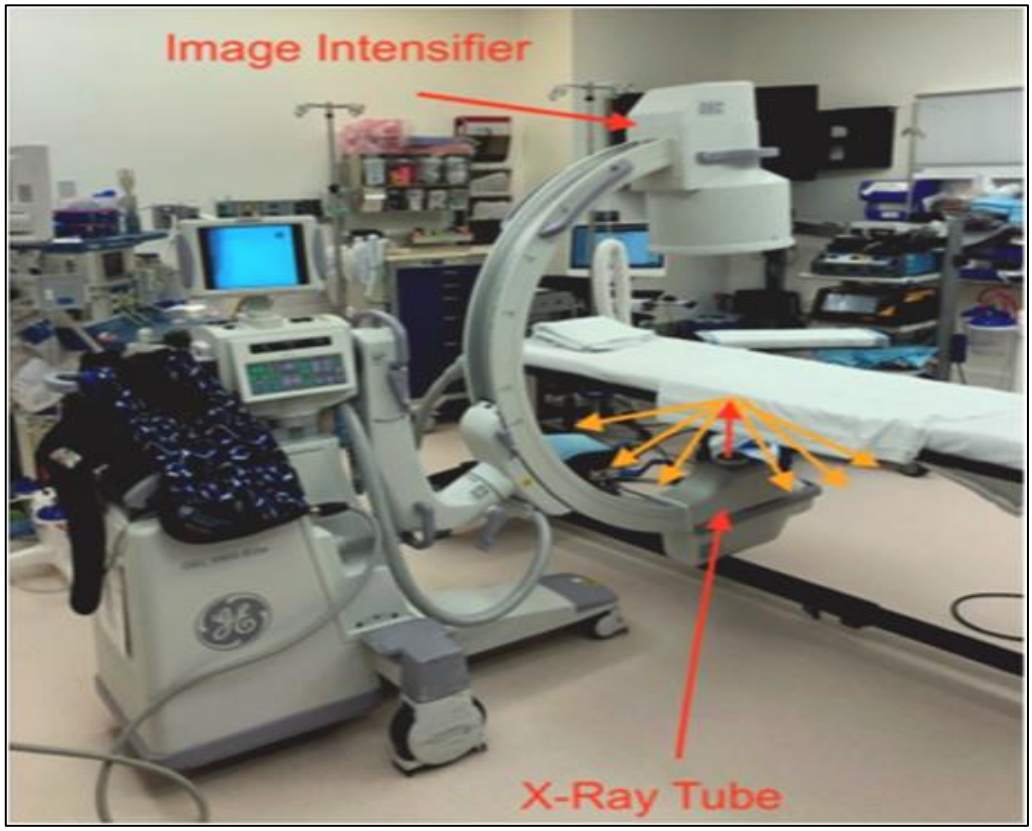

Figure 1: Correct positioning with the X-ray tube below the patient and table and the image intensifier above the patient.[1]

Practical recommendations include using pulsed fluoroscopy as the default mode, choosing the lowest acceptable pulse rate (4-7 pulses/sec), and ensuring that surgical teams are trained to adjust settings according to clinical needs. Verbal cues such as "X-ray on" improve team awareness during imaging. Incorporating pulsed fluoroscopy and optimal positioning protocols into daily orthopaedic workflows represents a high-impact, low-cost intervention that reduces radiation exposure without affecting surgical efficiency or outcomes.[8,11]

RADIATION AND PREGNANCY

Radiation exposure during pregnancy presents a critical concern for female orthopaedic surgeons, residents, and theatre staff. The degree of fetal risk depends largely on the gestational stage at the time of exposure. The first trimester, particularly the first 7 weeks of organogenesis, is the most vulnerable period, during which radiation can result in miscarriage, congenital malformations, or growth retardation. During the second trimester (8-17 weeks), the fetus remains sensitive, particularly in terms of central nervous system and skeletal development. By the third trimester (after 25 weeks), the relative risk decreases, and surgery, if unavoidable, is preferably undertaken during this period with adequate safety measures.[6]

Pregnant healthcare workers should adhere to strict radiation protection protocols. Double dosimetry is recommended, with one badge worn under the lead apron to estimate fetal dose and another outside the apron to monitor personal exposure. Standard protective gear, including a 0.5 mm lead apron, thyroid collar, and leaded glasses, must always be used. Non-scrubbed pregnant staff should maintain at least a two-meter distance from the X-ray source whenever possible, as this drastically reduces scatter exposure in accordance with the inverse square law.[7,12] In addition, pulsed fluoroscopy and beam collimation should be employed to further minimize radiation dose to both mother and fetus.[11]

The ICRP recommends that fetal exposure during pregnancy should not exceed 1 mSv, with special care during the first trimester. The annual occupational limit for pregnant workers remains 20 mSv, but closer monitoring and stricter safety practices are advised in this group.[6,28] Concerns regarding termination of pregnancy after accidental exposure are often overstated; according to ICRP guidelines, termination is not justified if fetal dose is below 100 mSv. Furthermore, extremity X-rays during pregnancy are generally considered safe, as the distance from the fetus and use of shielding minimize exposure.[6]

Proper education, strict adherence to institutional policies, and supportive scheduling practices are essential to ensure that pregnant orthopaedic personnel can continue their professional responsibilities safely without undue radiation risk.

MONITORING AND DOSIMETRY

Radiation monitoring is a crucial component of occupational safety for orthopaedic surgeons and theatre staff. The primary tool for monitoring is the thermoluminescent dosimeter (TLD) badge, which provides an accurate measurement of cumulative radiation exposure over time.[8,16] These badges are lightweight, easy to wear, and should be positioned on the chest outside the lead apron to record the effective dose. For pregnant workers, an additional badge is recommended under the lead apron at abdominal level to specifically monitor fetal exposure.[6]

The ICRP recommends an occupational radiation limit of 20 mSv per year, averaged over 5 years, with no single year exceeding 50 mSv.[28] However, studies have shown that most orthopaedic surgeons significantly underestimate their cumulative exposure, often neglecting to wear TLD badges regularly, thereby compromising long-term safety.[9,12,16] Proper adherence to monitoring protocols is essential, as cumulative exposure may lead to stochastic effects such as malignancy and genetic mutations, which do not have a threshold dose.[10,15]

In addition to personal dosimetry, some institutions advocate for area monitoring within operating theatres to assess scatter radiation levels in high-use fluoroscopy rooms. Regular calibration of X-ray machines and preventive maintenance further ensure radiation dose optimization. The use of real-time electronic dosimeters is gaining popularity, allowing immediate feedback to surgeons and encouraging behavioural changes to minimize unnecessary exposure.[27]

Despite these available measures, compliance with dosimetry remains poor in many centres due to lack of awareness, negligence, or inadequate enforcement of hospital policies. Therefore, routine education, strict enforcement of monitoring protocols, and regular review of exposure records are essential to promote a culture of radiation safety in orthopaedic practice.[12,16]

EDUCATIONAL RECOMMENDATIONS

While technology and protective equipment are vital in minimizing radiation exposure, awareness and training form the backbone of sustainable radiation safety in orthopaedic surgery. Unfortunately, formal teaching on this subject remains inconsistent in many training programs.

CURRENT GAPS IN EDUCATION

Most orthopaedic residents receive little or no formal instruction on radiation protection. Operating theatre staff often lack understanding of basic safety principles like ALARA or collimation. Compliance with protective equipment use is poor due to lack of awareness rather than resource scarcity.

RECOMMENDED EDUCATIONAL STRATEGIES

Integrate radiation safety into PG curriculum

Include lectures, workshops, and OT demonstrations. Assess knowledge through objective questions and simulations.

Mandatory radiation safety training for OT staff

Annual refresher sessions on equipment handling and protection measures. Posters and infographics displayed in OT areas.

Regular audits and feedback

Monitor compliance with lead gear use and dosimeter wear. Share feedback with individual surgeons and staff to reinforce best practices.

Simulation-based learning

Use low-dose practice scenarios to train surgical teams on optimal C-arm usage.

Interdisciplinary collaboration

Involve radiologists and physicists in teaching sessions to provide a broader perspective.

By institutionalizing radiation education at all levels-from residents to consultants-hospitals can dramatically improve compliance and reduce preventable exposure risks.

TAKE-HOME MESSAGES

To ensure radiation safety in orthopaedic surgery, the following practical points must be adopted universally by surgeons, residents, and operation theatre personnel.

PRACTICAL GUIDELINES FOR RADIATION SAFETY

Always follow the ALARA principle – minimize time, maximize distance, and use effective shielding. Use pulsed fluoroscopy over continuous mode to reduce radiation by up to 64%. Position the C-arm correctly – image intensifier above and X-ray tube below the patient. Wear protective gear consistently:Lead apron (0.5 mm thickness), thyroid shield, leaded eye glasses and lead gloves (when necessary). Keep hands out of the radiation beam and avoid holding instruments during exposure. Maintain a minimum 1-2 meter distance from the radiation source whenever possible. Use collimation to limit the field of exposure and improve image quality. Use dosimeters (TLD badges) and participate in regular exposure monitoring. Educate all OT personnel on basic radiation safety practices and equipment handling. Pregnant surgeons should take extra precautions, use double

dosimetry, and ideally operate in the third trimester if necessary.

Radiation exposure is a preventable occupational hazard. Adherence to these guidelines ensures not only personal safety but also improves institutional safety standards, making orthopaedic practice more sustainable and responsible.

CONCLUSION

Radiation exposure during orthopaedic procedures remains a significant yet preventable occupational hazard. The widespread use of X-rays and C-arm fluoroscopy necessitates strict adherence to protective strategies, including minimizing fluoroscopy time, optimizing C-arm positioning, and consistent use of shielding equipment such as lead aprons, thyroid collars, and lead glasses. Despite the availability of these measures, compliance continues to be suboptimal, largely due to inadequate awareness, insufficient training, and lack of enforcement of institutional policies.

Implementing structured education programs, routine monitoring with dosimetry, and reinforcement of the ALARA principle are vital to reducing exposure risk. Hospitals must take an active role in promoting a culture of safety through regular training workshops, provision of adequate protective equipment, and real-time feedback mechanisms such as electronic dosimetry. Special attention should be given to vulnerable groups, including pregnant healthcare workers, who require additional precautions and monitoring.

Ultimately, radiation safety in orthopaedic surgery depends not only on individual vigilance but also on systemic institutional commitment. By fostering a safety-conscious environment and ensuring accountability at all levels, the health of orthopaedic surgeons, operating theatre staff, and patients can be safeguarded effectively. This review highlights the urgent need to translate knowledge into practice, thereby advancing occupational safety standards in orthopaedic surgery worldwide.

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