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Review Article

Radiation Exposure During Intramedullary Nailing of Femoral and Tibial Fractures: How Much Radiation Does an Orthopedic Surgeon Receive and Habits to Reduce Radiation Exposure

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Abstract

Radiation exposure is omnipresent in the orthopedic field, especially with the advent of minimally invasive techniques such as intramedullary nailing. A thorough understanding of radiation is necessary due to the health effects of accumulating exposure. In this review, we discuss radiation with a focus on the radiation exposure during the intramedullary nailing of femoral fractures and tibial fractures. We also discuss habits to reduce radiation exposure in the operative room and adhere to the principle of keeping operative radiation exposure "as low as reasonably achievable." With a thorough understanding of radiation and habits to reduce radiation exposure, an orthopedic surgeon can safely navigate treating these long bone fractures.

Keywords: Radiation Exposure; Radiation Dose; Intramedullary Nailing; Femoral; Tibial; Fluoroscopy; Personal Protective Equipment

Abbreviations

IMN: Intramedullary Nailing; Gy: Gray; Sv: Sievert; DNA: deoxyribonucleic acid; ICRP: International Commission on Radiological Protection; NCRP: National Council on Radiation Protection & Measurements; ALARA: As Low as Reasonably Achievable; PPE: Personal Protective Equipment

Introduction

With the advent of minimally invasive techniques in orthopedics, such as intramedullary nailing (IMN), the importance of intraoperative imaging has become critical for successful operative treatment. However, less surgical exposure often requires more intraoperative imaging, which in turn predisposes the operative staff to increased radiation exposure [1]. In this review, we discuss background knowledge on radiation, literature describing how much radiation exposure a surgeon receives during IMN of femoral and tibial fractures, and habits to reduce radiation exposure.

Radiation background knowledge

X-rays represent electromagnetic radiation with a wavelength on the scale of 0.01 to 10nm, which make x-rays have a wavelength longer than gamma rays, but shorter than ultraviolet rays. When x-rays are created, they can either pass through, become absorbed, or scatter when they hit a tissue depending on the x-ray energy and the attenuation coefficient of the tissue. Due to the high attenuation coefficient of calcium, the photons from the x-rays are absorbed by bone, which results in a negative image of bone. As mentioned, some of the photons scatter, and this scattering can occur in multiple directions. Because surgeons and operative staff are not directly in the path of the x-ray beam, scatter radiation represents the predominant source of occupational radiation exposure [1,2].

Two International System of Units exist to describe ionizing radiation depending on the context, which include the gray (Gy) and the sievert (Sv). The gray represents 1 joule of radiation energy per kilogram of matter and is an actual physical quantity. The gray describes the absorbed radiation dose but does not express the type of energy nor the type of tissue exposed. On the other hand, the sievert represents the potential biologic effect of 1 joule of radiation energy per kilogram of mass. The sievert differs from the gray in that it also considers the type of radiation and the type of tissues the radiation is affecting. For example, each tissue in the body has a tissue weighting factor which is incorporated when determining the total amount of sieverts [2].

The effects of radiation exposure on an individual can be categorized as either deterministic effects or stochastic effects. Deterministic effects result when a certain threshold of photons is absorbed, which results in a large number of cells dying within a certain organ or tissue. Examples of deterministic effects include skin erythema, hematopoietic change, fibrosis, hair loss, and cataracts. Deterministic effects can occur either after a single high-dose radiation exposure or after repeated low-dose exposures, as each photon absorbed leads to tissue damage until a threshold is met to cause a tissue health effect. On the other hand, stochastic effects arise from low-dose radiation that damages deoxyribonucleic acid (DNA) and raises the probability of a health effect occurring. Unlike a deterministic effect, there is no threshold where a health effect will definitely occur, and the severity of the health effect does not change with increases in radiation dose. However, the likelihood of a stochastic effect simply occurring does increase with increases in radiation dose. Cancer represents the typical stochastic effect example, as every incremental increase in radiation damage to the DNA results in an increased likelihood of developing an oncogenic mutation [1,2].

The International Commission on Radiological Protection (ICRP) and the United States National Council on Radiation Protection & Measurements (NCRP) represent two organizations that set radiation safety metrics. The ICRP endorses a maximal occupational radiation exposure of 20 millisieverts (mSv) per year, while the NCRP recommends a maximal occupational radiation exposure of 50 mSv per year. These thresholds are mainly based on linear extrapolations from studies following the survivors of the atomic bombings in Hiroshima, Japan and Nagasaki, Japan. With these thresholds in mind, a surgical principle that has developed is to keep the operative radiation usage "as low as reasonably achievable", which has been shorthanded to the term "ALARA" [2].

How much radiation exposure is there during IMN?

Radiation exposure during femoral IMN

Fuchs., *et al.* conducted a study assessing how much radiation exposure an orthopedic surgeon experiences during various orthopedic procedures. One of the procedures they assessed was femoral IMN, in which they measured the radiation dose in 8 cases. Fuchs., *et al.* found that the average operative time was 135 minutes, the average fluoroscopy time was 450 seconds (range, 255-708 seconds), and the average radiation exposure derived from the dosimeters was 19.0 Sv in the eye, 35.4 Sv in the thyroid, and 41.7 Sv in the hands. The authors concluded that the radiation exposure on the scale of Sv (10^{-6}) was safe and far below the threshold levels of mSv (10^{-3}) [3].

Madan., *et al.* assessed the radiation exposure in 85 cases of femoral IMN and studied the effect of multiple factors. First, Madan., *et al.* noted that a surgeon's experience significantly affected the total radiation time, with consultant orthopedic surgeons needing 0.52 minutes of radiation time for femoral IMN compared to middle-grade orthopedic surgeons needing 1.61 minutes ($p < 0.05$). When comparing IMN type utilized, the Russel-Taylor IMN required 0.52 minutes of radiation time, whereas the Marchetti-Vincenzi IMN required 0.20 minutes of radiation time ($p < 0.05$). Madan., *et al.* also reported on the effect of distance with regard to radiation exposure of a surgeon's hand. The authors found that the radiation dose to the surgeon's hand at 15 cm, 30 cm, and 60 cm from the x-ray source was 1.272 mSv, 0.314 mSv, and 0.080 mSv, respectively. Finally, the authors also tracked the radiation dose a patient's gonads received during femoral IMN, since much of the fluoroscopy shots involve this patient area. Madan., *et al.* found that the patient's had a radiation dose of 1.36 mSv to their gonadal region and concluded that efforts should be made to protect this patient area with lead during femoral IMN [4].

Patra., *et al.* reported the radiation exposure a surgeon, surgical assistant, and scrub nurse received during femoral IMN and then assessed their data according to the surgeon's level of experience. The authors found that the average radiation dose to the surgeon, surgical assistant, and the scrub nurse was 79.9 Sv, 30.9 Sv, and 12.5 Sv for consultants performing the surgery, 110.1 Sv, 66.7 Sv, and 20.4 Sv for senior registrars performing the surgery, and 181.6 Sv, 113.6 Sv, and 37.1 Sv for trainees performing the surgery, respectively [5].

Noton., *et al.* performed a study on whether there is a difference in radiation exposure between treating with a long femoral IMN versus a short femoral IMN. The authors retrospectively assessed 108 patients, with 45 undergoing short IMN (TFNA-Synthes) and 63 undergoing long IMN (RAFN, LFNA, or TFNA-Synthes). There was a significant difference with regard to mean radiation dose, with the short IMN group having a radiation dose of 7.350 mGy versus 10.915 mGy for the long IMN group ($p = 0.012$). Moreover, the mean radiation time was 1:32 minutes for the short IMN group compared to 2:32 minutes for the long IMN group. Noton., *et al.* concluded that the short IMN should be employed to reduce radiation exposure when the fracture pattern and clinical scenario allow [6].

Radiation exposure during tibial IMN

Madan., *et al.* analyzed the radiation exposure in 99 cases of tibial IMN and categorized their data by multiple factors. The authors first assessed the impact of surgical experience and found that the mean radiation time for the consultant orthopedic surgeons was 0.56 minutes and significantly less compared to the middle-grade orthopedic surgeons who had a mean radiation time of 1.28 minutes ($p = 0.03$). The authors next assessed the effect of the IMN type on the radiation exposure and found that the Marchetti-Vincenzi tibial IMN required a significantly less radiation time of 0.22 minutes compared to the 0.56 minutes for the Russell-Taylor tibial IMN ($p = 0.0046$). Finally, Madan., *et al*. reported on the effect of distance with regard to the radiation exposure of a surgeon's hand. The authors found that the radiation dose to the surgeon's hand at 15 cm, 30 cm, and 60 cm from the x-ray source was 0.330 mSv, 0.081 mSv, and 0.021 mSv, respectively [4].

Patra., *et al*. recorded the amount of radiation exposure a surgeon, surgical assistant, and scrub nurse received during tibial IMN and further categorized their data according to the surgeon's level of experience. The authors found that the average radiation dose to the surgeon, surgical assistant, and the scrub nurse was 13.6 Sv, 7.4 Sv, and 1.5 Sv for consultants performing the surgery, 14.5 Sv, 8.1 Sv, and 1.6 Sv for senior registrars performing the surgery, and 15.2 Sv, 9.2 Sv, and 2.0 Sv for trainees performing the surgery, respectively. The authors concluded that a surgeon encounters the most radiation exposure compared to assistants and scrub nurses, and that increasing surgical experience results in decreased radiation exposure [5].

Jobson., *et al*. studied the radiation exposure in 102 tibial fractures treated with IMN. The authors found that the average radiation exposure was 2.38 Gy-cm^2 (range, 0.01-13.07 Gy-cm^2). When dichotomizing by approach, the authors found the average radiation exposure to be 2.13 Gy-cm^2 in 61 cases with the suprapatellar approach, and 2.23 Gy-cm^2 in 41 cases with the infrapatellar approach. The authors also categorized their data by fracture classification using the Müller AO Classification and identified no statistically significant difference for radiation exposure between the different fracture patterns ($p = 0.08$). Finally, Jobson., *et al*. also assessed the effect of surgical experience on radiation exposure designating three groups with different levels of experience: 1) group 1 with >8 years of experience, 2) group 2 with 6-8 years of experience, and 3) group 3 with 1 – 5 years of experience. Interestingly, there was no statistically significant difference between any of the groups with regard to radiation exposure ($p = 0.65$). Moreover, there was also no significant difference when the data was categorized by both the fracture pattern and the surgical level of experience ($p = 0.17$) [7].

Williamson., *et al*. also assessed the influence of approach with regard to radiation exposure during tibial IMN in 90 cases. In 53 suprapatellar approaches, the authors found a mean fluoroscopy time of 94.4 ± 47.9 seconds and a radiation dose of 38.2 ± 26.7 cGy-cm^2. In 37 infrapatellar approaches, the authors found a mean fluoroscopy time of 129.7 ± 56.6 seconds and a radiation dose of 53.6 ± 34.3 cGy-cm^2. The suprapatellar approach group had significantly reduced fluoroscopy time ($p = 0.002$) and radiation dose ($p = 0.02$). The authors concluded that the suprapatellar approach results in less radiation exposure to the surgeon, assistants, and patient compared to the infrapatellar approach in surgeons experienced in both approaches [8].

Habits to reduce radiation exposure

The habits to reduce radiation exposure generally categorize to 1) the position of the fluoroscopy machine, 2) the distance from the x-ray source, 3) reducing the radiation dose generated, and 4) personal protective equipment (PPE).

Position of the fluoroscopy machine

As discussed, the majority of radiation exposure to the operative staff derives from scatter radiation. In general, the scatter radiation is going to commonly reflect back towards the x-ray source, and this is important to consider when orienting the C-arm fluoroscopic machine. When positioning the C-arm, one should place the x-ray tube below the operative table and the image intensifier above the patient. This configuration allows the scatter radiation to reflect downwards and away from the operative staff's torso and cephalad region (Figure 1) [9].

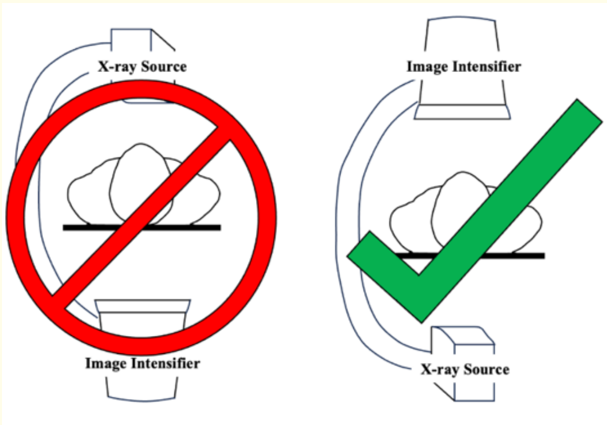

Figure 1: Proper positioning of the fluoroscopy machine is with the x-ray source below the operative table and the image intensifier above the patient.

The principle that the scatter radiation generally reflects back towards the x-ray tube also comes into play when conducting cross-table imaging. With cross-table imaging, the operative staff should stand on the side with the image intensifier to minimize exposure, as the scatter radiation will mainly reflect in the other direction (Figure 2) [9]. Rampersaud., *et al*. found that the surgeons who stood on the side of the image intensifier as opposed to the x-ray tube received 3-4 times less radiation to their thyroid [10].

In addition to considering where the x-ray tube and image intensifier are positioned in space, the position of the patient's body in relation to the C-arm also plays a role. The radiation dose to the

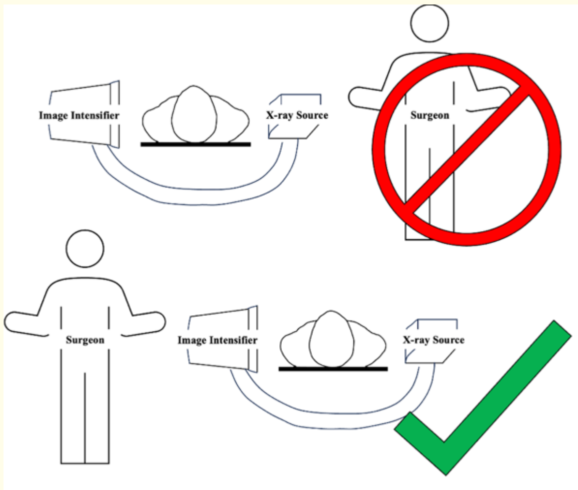

Figure 2: Proper positioning of the operative staff with cross-table imaging is with the operative staff standing on the side of the image intensifier.

patient and the scatter radiation are reduced when the patient's body is placed as close to the image intensifier and as far from the x-ray tube as ergonomically possible (Figure 3) [9].

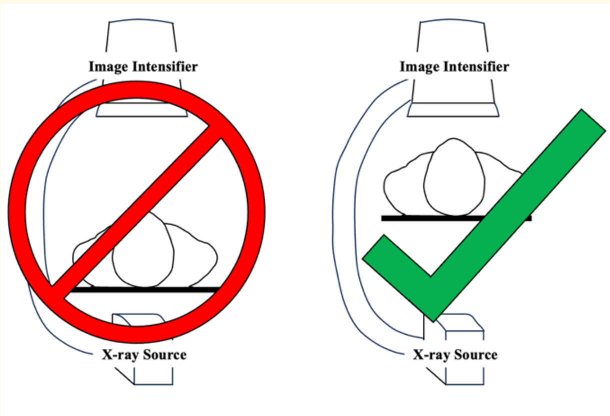

Figure 3: Proper positioning of the fluoroscopy machine with the patient's body close to the image intensifier and far from the x-ray source.

Finally, it is common in orthopedic procedures to take iterative fluoroscopic images to check reductions, hardware position, and the like, so one can help reduce the number of fluoroscopic images needed by utilizing quick ways to position the fluoroscopic machine and obtain these desired images. One way is to mark the floor with adhesive tape to remember the position of the fluoroscopic machine. In this way, when the fluoroscopic machine is moved to take another image, but then is needed to take the same image that was taken before, the adhesive tape on the floor can serve as a guide to quickly position the fluoroscopy machine and reduce taking unnecessary fluoroscopic images. A laser target can also facilitate proper positioning to take fluoroscopic images and minimize the trial-and-error aspect of obtaining a perfect image [9].

Freezing the last fluoroscopic image taken on the monitor, otherwise known as an "image hold", can also help minimize the need for excess fluoroscopic shots. The image hold allows a surgeon to critically plan his or her next maneuver with having an image to refer to. This strategy eliminates the need for excess fluoroscopic shot to refresh a surgeon's conceptualization [1].

Distance from the x-ray source

Scatter radiation follows Newton's inverse square law, which is the fact that radiation exposure is inversely proportional to the square of the distance from the x-ray source. In other words, the radiation exposure can be exponentially reduced if the operative staff stands further away from the x-ray source; small distances can have great effects (Figure 4) [2]. Raffetto., *et al*. found that the radiation exposure decreases by 94% and 98% when a surgeon stands 3 feet away and 6 feet away from the x-ray source compared to when a surgeon stands next to the x-ray source [11]. Hsu., *et al*. found that the scatter radiation dose is <0.3% of that of the direct radiation beam when one stands at least 1 foot away from the x-ray source [12]. Also, it important to be cognizant that larger masses, such as the torso or certain body parts in obese patients with a large body habitus, are more likely interact with an increased number of x-rays and result in more scatter radiation making distance from the x-ray source become more paramount [2].

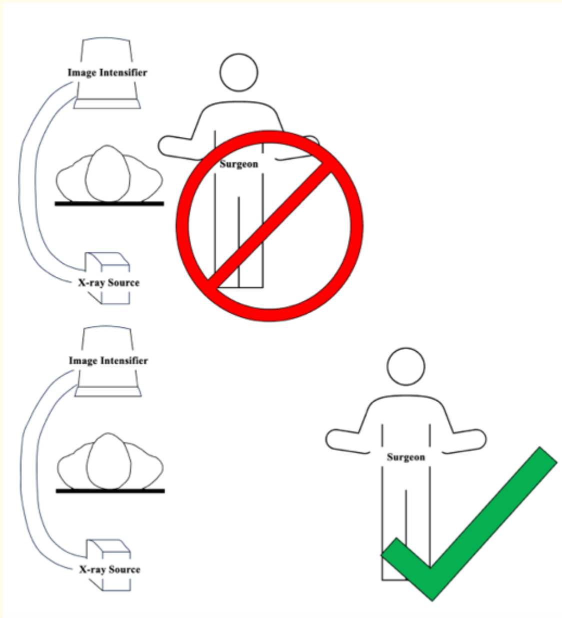

Figure 4: Proper positioning of the operative staff with the operative staff standing away from the x-ray source.

Reducing the radiation dose generated

Two main ways to reduce the radiation dose generated with fluoroscopy machine include the use of collimators and the use of pulsed fluoroscopy.

Collimators, or lead shutters, allow one to reduce the radiation dose by concentrating on the image target and only letting out a radiation beam on the specific anatomic point of interest. In addition to irradiating a smaller area on the patient, the smaller beam let out with collimation also reduces the amount of scatter radiation reflected. Yamashita., *et al*. found that the amount of radiation to a surgeon's hand and thyroid with collimated fluoroscopy was reduced by approximately 65% compared to non-collimated fluoroscopy [13].

Pulsed fluoroscopy, now available with modern technology, offers another way to reduce the radiation dose. Historically, fluoroscopy machines only shot in continuous mode in such a way that only a continuous x-ray beam could be shot. Nowadays a fluoroscopic machine can pulsate the x-ray beam at a selected pulse rate to not only reduce the radiation dose, but also improve the image quality [14]. Yamashita., *et al*. reported that the use of pulsed fluoroscopy (at a rate of 8 times per second) reduced the radiation dose by 30% to the patient, and by 70% to the surgeon's hand and thyroid gland [13].

Personal protective equipment (PPE)

Personal protective equipment in the form of lead aprons, lead thyroid shields, lead eyeglasses, and more can help reduce radiation exposure and should be worn in all operative cases requiring fluoroscopy.

Lead aprons greatly diminish the scatter radiation to the thorax with the exact amount of attenuation dependent on the fluoroscopic machine's kilovoltage setting and whether the apron's lead is 0.25mm thick versus 0.5mm thick. A 0.25mm thick lead apron attenuates 90% of radiation and a 0.5mm thick lead apron attenuates 99% of radiation [15,16]. Furthermore, a 0.5mm thick lead apron can reduce radiation exposure from 0.10 mSv to 0.001 mSv during femoral IMN, which essentially nullifies the radiation risks associated with the thorax [15-17]. When wearing a lead apron, circumferential lead should be worn as opposed to non-circumferential lead. Raffetto., *et al*. found that when a surgeon wears a non-circumferential lead apron and faces toward the radiation source, the radiation dose is 0.95 R/10s. However, when the surgeon turns around and faces away from the radiation source as to no longer be protected by the noncircumferential lead apron, the radiation dose is significantly increased by 98% to be 48.1 R/10s ($p < 0.001$). Moreover, when a surgeon stands perpendicular to the radiation source, the radiation dose is significantly increased by 22% to be 37.7 R/10s ($p < 0.001$). Thus, Raffetto., *et al*. concluded that circumferential lead should be worn to prevent dangerous cumulative radiation exposure throughout an orthopedic career [11].

Lead thyroid shields should be employed at all times in IMN cases of femoral and tibial fractures, as one study found that the average radiation dose without a thyroid shield was 70 times more than with a thyroid shield [18]. The ICRP thyroid radiation exposure limit is 300 mSv per year [9]. Lee., *et al*. performed a study assessing the difference in radiation exposure between lead thyroid shields versus lead-equivalent thyroid shields, as well as the effect of how tightly versus how loosely a thyroid shield is worn and also the effect of including a bismuth masking reagent. The authors found that for within the lead thyroid shield group, the tightly worn shield group, the loosely worn shield group, and the loosely worn shield group with a bismuth masking reagent resulted in 1.91 ± 0.13 Sv/min, 2.35 ± 0.22 Sv/min, and 1.86 ± 0.13 Sv/min, respectively. Wearing the lead thyroid shield tightly or wearing the thyroid shield loosely with the bismuth masking reagent resulted in significantly less radiation exposure compared to wearing the lead thyroid shield loosely alone without the bismuth masking reagent ($p < 0.001$). For the lead-equivalent thyroid shield group, the radiation doses for the same groups as listed above were 1.79 ± 0.12 Sv/min, 1.82 ± 0.11 Sv/min, and 1.74 ± 0.12 Sv/min, respectively. The authors found no significant difference between these groups within the lead-equivalent thyroid shield group. Finally, Lee., *et al.* found that the amount of radiation exposure to the unshielded thyroid on average was 16.32 ± 0.48 Sv/min. The authors concluded that wearing the thyroid shield tightly, or if the tightness is uncomfortable, wearing the thyroid shield loosely with a bismuth masking reagent can reduce the radiation dose to the thyroid [19].

Lead eyeglasses should be worn as they reduce the ocular radiation exposure to a surgeon by 90% [20]. The ICRP ocular radiation exposure limit is 20 mSv per year averaged over 5 years or a maximum of 50 mSv in any single year. Thus, since a femoral IMN results in approximately 0.05 mSv per case, it would take 400 femoral IMNs per year to reach the ICRP limit without lead glasses [15,17,21]. However, the consistent use of lead eyeglasses decreases the radiation exposure by one order of magnitude and theoretically eliminates the chance of the ICRP limit being reached and or any risk of the radiation exposure reaching levels to cause cataracts [2].

Conclusion

Orthopedic surgeons are consistently exposed to radiation, and this is when treating femoral and tibial fractures with IMN. Thus, an understanding of the basic knowledge of radiation, how much radiation is associated with IMN procedures, and habits to reduce radiation exposure are critical to one's safety. In this review, we discuss these topics to educate the orthopedic surgeon treating these fractures.

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