Elevated Radiation Exposure Associated With Above Surface Flat Detector Mini C-Arm Use

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Dennis P. Martin¹, Talia Chapman¹, Christopher Williamson¹,
Brian Tinsley¹, Asif M. Ilyas¹, and Mark L. Wang¹

Abstract

Background: This study aims to test the hypothesis that: (1) radiation exposure is increased with the intended use of Flat Surface Image Intensifier (FSII) units above the operative surface compared with the traditional below-table configuration; (2) this differential increases in a dose-dependent manner; and (3) radiation exposure varies with body part and proximity to the radiation source. **Methods:** A surgeon mannequin was seated at a radiolucent hand table, positioned for volar distal radius plating. Thermoluminescent dosimeters measured exposure to the eyes, thyroid, chest, hand, and groin, for 1- and 15-minute trials from a mini C-arm FSII unit positioned above and below the operating surface. Background radiation was measured by control dosimeters placed within the operating theater. **Results:** At 1-minute of exposure, hand and eye dosages were significantly greater with the flat detector positioned above the table. At 15-minutes of exposure, hand radiation dosage exceeded that of all other anatomic sites with the FSII in both positions. Hand exposure was increased in a dose-dependent manner with the flat detector in either position, whereas groin exposure saw a dose-dependent only with the flat detector beneath the operating table. **Conclusions:** These findings suggest that the surgeon's hands and eyes may incur greater radiation exposure compared with other body parts, during routine mini C-arm FSII utilization in its intended position above the operating table. The clinical impact of these findings remains unclear, and future long-term radiation safety investigation is warranted. Surgeons should take precautions to protect critical body parts, particularly when using FSII technology above the operating with prolonged exposure time.

Keywords: eye radiation, flat detector, fluoroscopy, hand radiation, mini C-arm, radiation

Introduction

The utilization of mini C-arm fluoroscopic units with Flat Surface Image Intensifier (FSII) technology is rising in the ambulatory surgery setting. Similar to standard mini C-arm units, those with FSII technology offer several advantages over that of the traditional large C-arm, including cost-effectiveness, ease of maneuverability and storage, less scatter of ionizing radiation, and obviating the need for a dedicated radiology technologist.^{1,2,6,10,11,13,15,16} Moreover, the ability to image above the operating surface using FSII technology offers the practical feature of increasing the surgeon's functional operating space, better accommodating implant instrumentation and powered equipment. As a result, these features have increased the popularity of implementing FSII units with common hand surgery procedures, as well as lower extremity procedures, such as ankle fracture fixation.

To date, the amount of fluoroscopic radiation exposure to the surgeon associated with the routine use of this newer technology has yet to be determined. Specifically, the radiation load to critical body parts, including the operator's eyes, thyroid, chest, hands, and groin, is presently unknown and remains concerning due to: (1) the potential for increased scatter of ionizing radiation above the operating table; and (2) the proximity of the operator's head below the fluoroscopic radiation emitting source, when utilized in the intended above surface configuration.

¹Department of Orthopedic Surgery, The Rothman Institute, Sidney Kimmel Medical College, Thomas Jefferson University, Philadelphia, PA, USA

Corresponding Author:

Mark L. Wang, Associate Professor, Division of Hand Surgery, Department of Orthopedic Surgery, The Rothman Institute, Sidney Kimmel Medical College, Thomas Jefferson University, 925 Chestnut Street, Philadelphia, PA 19107-1216, USA.
Email: mark.wang@rothmaninstitute.com

Figure 1. Surgeon mannequin seated at a radiolucent hand table, positioned for volar distal radius plating with the flat mini c-arm (a) above and (b) below the table. Thermoluminescent dosimeters measured radiation exposure to the surgeon's eyes, thyroid, chest, hand, and groin.

This study aims to test the hypothesis that: (1) radiation exposure is increased with the intended use of FSII units above the operative surface compared with that of the traditional below-table configuration; (2) this differential in radiation dosage is further increased in a dose-dependent manner; and (3) radiation exposure varies with specific body part and proximity to the radiation emitting source.

Methods

Dosimeter Placement

An anthropomorphic surgeon model (MD-HMB2FK; Roxy Display, East Brunswick, New Jersey) was outfitted with surgical glasses (SurgiTel, Ann Arbor, Michigan), surgical cap and mask (Medline, Mundelein, Illinois), lead apron and thyroid shield (Burlington Medical Supplies, Newport News, Virginia) to simulate the form of a live surgeon (Figure 1). In place of a surgical gown, a lead apron was used to provide a more stationary surface for dosimeter placement and exchange between trials. Thermoluminescent dosimeters (Landauer, Glenwood, Illinois) were placed on the model in 5 locations. Four badge dosimeters were placed between the eyes on the lower forehead, on the neck overlying the thyroid, on the chest at the midline of the sternum and the level of the fourth ribs, and the groin. A ring dosimeter was placed over the proximal phalanx of the right index finger.

Positioning

As previously described by Hoffler and Ilyas,⁷ the anthropomorphic model was seated at a radiolucent hand table in an operating position. A Sawbones wrist model (Pacific Research Laboratories, Vashon, Washington) with a volar-plated distal radius was placed on the hand table with the volar plate (2.4-mm LCP; Synthes, Paoli, Pennsylvania) in the center of the fluoroscopy beam. The model's hands

rested in pronation on either side of the volar plate, with the distal phalanges of its index fingers positioned 40 cm apart.

Fluoroscopy Settings and Recording

A mini C-arm FSII unit (OrthoScan, Scottsdale, Arizona) was evaluated in 2 configurations: (1) above the operating table, as intended; and (2) in the traditional below-table position, associated with the typical use of standard mini C-arm units (Figure 1). In the below-table position, the volar distal radius plate was 25 cm directly below the fluoroscopy source, whereas in the above table configuration, the distance from the source to volar plate was 30 cm. Horizontal, vertical, and direct distances from the radiation emission source to each dosimeter were measured. The fluoroscope voltage was set to 60 kVp, a value within a typical voltage range (between 50 and 60 kVp) at our institution. Current, typically ranging from 65 to 105 μ A, was automatically set to 74 μ A. The fluoroscopic testing was evaluated for 1 minute, representing the mean cumulative fluoroscopy time for distal radius fracture volar plating procedures at our institution, and 15 minutes, representing an estimate of a hand surgeon's cumulative monthly exposure at each position.⁷ With fluoroscopic output settings kept constant, the fluoroscope scanned the wrist model for 3 separate continuous 1-minute and 15-minute trials with the FSII positioned above the operating surface. Exposure assays were then repeated with the unit positioned below the table. Test dosimeters were replaced after each trial. Background radiation was measured via control dosimeters, placed in the corner of the operating room at a distance of 3.5 meters from the source, and subtracted from the test dosimeters.

Statistical Analysis

Prior to initiating the study, a power analysis was performed to ensure adequate power for the planned assays (power set at 80%, with $P < 0.05$). Parametric paired t tests were used

Figure 2. (a) At 1 minute of exposure, both the eye and hand absorb a higher dosage of radiation (mrem) when the flat c-arm is positioned above vs below the table. (b) At 15 minutes of exposure, only the hand receives a significant dose of radiation (mrem) in both flat C-arm positions.

* $P < 0.05$, **** $P < 0.0001$.

to compare the cumulative radiation exposure at each anatomic site between the Above vs Below configuration groups, and between the 1-minute vs 15-minute exposure time groups. Analysis of variance compared cumulative exposure between the various anatomic sites. Alpha was set to 0.05, and a trend was defined at $P < 0.1$. All values are expressed as mean values $\pm$ the standard error of the mean.

Results

One-minute cumulative exposures to the hand and eye were significantly greater with the flat detector positioned above the table compared with below ($P = 0.049$ and $P = 0.007$). At 15-minutes of exposure, hand radiation dosage exceeded that of all other anatomic sites with the C-arm positioned above ($P < 0.001$; 95% confidence interval [CI]) and beneath ($P < 0.001$; 95% CI) the table (Figure 2a). Hand exposure was increased in a dose-dependent manner, with 15-minute accumulated doses significantly greater than 1-minute doses with the flat detector above the operating surface and below ($P = 0.001$ and $P = 0.004$). Groin exposure revealed a dose-dependent increase from 1-minute to 15-minute exposure time with the flat detector beneath the operating table ($P = 0.047$; Figure 2b).

Discussion

The risk of excessive radiation exposure to critical body parts with the routine use of FSII mini C-arm fluoroscopy remains unknown, and its associated clinical impact on the long-term health of the surgeon is an expanding area of concern. With the use of this newer technology, the possibility exists for increased ionizing radiation to the operator: (1) directly from the primary emission source; and (2) secondary radiation scatter resultant from surrounding tissue, implants, or equipment within the path of the fluoroscopic

beam. The eyes, thyroid, breasts, gonads, and hands are particularly sensitive to ionizing radiation.^{8,14} Chronic radiation exposure has been linked to early-onset cataracts and up to 85% of all papillary thyroid carcinomas.⁵ Epidemiologic studies have shown a higher rate of cancers among orthopedic surgeons compared with age- and gender-matched peers,⁹ as well as an 85% higher prevalence of breast cancer in female orthopedic surgeons than the general female population.⁴

Prior clinical and simulation studies have reported significantly lower rates of scatter from a mini C-arm unit relative to the standard large C-arm, reporting that the scatter from the mini C-arm was eliminated with the use of lead shielding equipment.^{10,12} A simulation of mini C-arm-guided Hand Surgery by Giordano et al.⁶ found that only dosimeters placed directly in line with the fluoroscopic beam receive a substantial amount of exposure. Importantly, this zone is where the surgeon's hands are often placed for fracture reduction or limb positioning. Similarly, in an evaluation of hand exposure incurred by 5 practicing hand surgeons, Singer et al.¹⁰ concluded that the marked increase in radiation load to the surgeon's hands is related to their direct placement within the fluoroscopic beam. In concurrence with these prior reports, our findings here suggest that the surgeon's hands incur the greatest radiation exposure compared with other body parts, during routine mini C-arm FSII utilization in its intended position above the operating table. A lesser but significant increase was also observed with eye exposure compared with that of the thyroid, chest, and groin. These findings are consistent with similar anatomic differences reported by Hoffler and Ilyas.⁷

With fixed fluoroscopic output settings, radiation exposure from the primary beam is inversely proportional to the square of the distance from the source.⁷ In accordance with the inverse square law, we anticipated a lower mean exposure to the hand associated with the Above configuration,

given the hand dosimeter location 5.4 cm further from the fluoroscopic source. However, we observed significantly greater mean dosages to the surgeon's hand and eyes when the flat detector was above the operating table compared with that of the below position after 1-minute of live fluoroscopy. With this intended use of FSII technology, the potential for increased scatter from the flat image intensifier surface, as well as the absence of scatter attenuation by the hand table, may represent critical parameters to the elevated hand exposure observed in this study. Furthermore, with this configuration, the location of the eye directly below the radiation emission source may also be a contributing factor to the elevated eye dosages observed here. Last, we observed a trend in increased groin exposure associated with the below-table position, which may be explained by increased scatter from the flat detector in the absence of an intervening table.

Singer et al.¹⁰ previously reported no correlation between surgeons' cumulative fluoroscopy time and their measured radiation exposure; however, this study did not control for variations in fluoroscopic output settings. Vosbikian et al.¹⁵ reported that, in a prospective clinical study, mini C-arm usage resulted in greater fluoroscopic radiation output, longer exposure times, and greater radiation doses to the surgeon's hand compared with that of large C-arm units. Our findings here demonstrated dose-dependent increases in hand exposure with both configurations and elevated exposure to the groin with the below-table setting. Because radiation exposure is proportional to the kV peak squared (kVp^2) and to the milliamperere-seconds (mAs), which both remained constant throughout our assays, the relationship between exposure time and cumulative dose found in this study appears valid.

The International Commission on Radiological Protection recommends a limit of 50 rem occupational radiation exposure to the hand per year.¹⁷ The highest exposure rate recorded in our study was 14.0 mrem/min, with the flat detector above the table surface. At our institution, the mean fluoroscopy time for a volar plating procedure at our institution is 1 minute.⁷ At this maximum exposure rate, a surgeon would need to perform 3,571 of such procedures to approach this threshold. At the maximal rate of eye exposure reported in our study, 16.7 mrem over 15 minutes, a surgeon would need to perform 13,513 volar plating procedures before reaching the ICRP-recommended yearly limit of 15 rem. However, findings published by Chodick et al.³ suggest that as little as 6 rem of lifetime occupational exposure increases the practitioner's risk for cataracts compared with the general population by 25%. A surgeon would reach this threshold after 90 cumulative hours of fluoroscopy using a mini c-arm with FSII above the table, or 5,405 volar plating procedures over an entire career.

The aims of this study were successfully completed by creating a controlled environment where the only factors

permitted to change were the exposure time and position of the C-arm relative to the phantom operator and table. Test dosimeters were all analyzed at one time by an independent testing center, and background radiation, measured by control dosimeters, was subtracted from the test dosimeters. Despite these measures, this simulation is not without limitations. The dosimeters used in this study are designed to report cumulative radiation exposure over a period of several months and may lack the capacity to detect smaller differences across body parts over short exposure intervals. At present, dosimeters designed for single dose testing, which can be annealed for repeat use, are commercially available; however, their relative sensitivity to fixed radiation loads remains undetermined and requires further investigation. Future comparative trials among existing dosimeters may help determine the most suitable dosimeter for forthcoming studies. In addition, statistical power was limited to triplicate dosimeters for each experimental condition, and the possibility exists that larger sample sizes may potentially reveal smaller differences across thyroid, chest, and groin exposures under similar conditions. Last, this phantom study does not completely replicate live usage of FSII technology, where the operator may have the ability to create more distance between body parts and the fluoroscopic unit. However, during critical portions of a case, such as maintaining fracture reduction, the operator may not be able to sufficiently move the hands or eyes away from the fluoroscopic beam.

Compared with its predecessors, the mini C-arm with FSII technology offers the practical feature of increasing the surgeon's functional operative space. As with all fluoroscopy machines, excessive exposure to ionizing radiation to the surgeon and the surgical team remains an occupational risk factor with the use of such technologies. In this study, we report trends in radiation exposure to 5 anatomic sites that are relevant to the long-term health and career longevity of the orthopedic surgeon. Our findings suggest that, with the routine use of the flat mini C-arm in its intended position above the operating table, the surgeon's hands and eyes receive elevated radiation exposure compared with that of other body parts. While the links between radiation exposure, malignancy, and cataracts are well documented, the specific long-term effects and critical thresholds of fluoroscopic radiation exposure have yet to be elucidated and require further investigation. Surgeons should take precautions to protect critical body parts, particularly when using FSII technology above the operating surface with prolonged exposure time.

Ethical Approval

Each author certifies that The Rothman Institute at Thomas Jefferson University has approved the reporting of this study and that all investigations were conducted in conformity with ethical principles of research.

Statement of Human and Animal Rights

This article does not contain any studies with human or animal subjects.

Statement of Informed Consent

Informed consent was obtained when necessary.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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