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The Effect of Metal Instrumentation on Patient and Surgical Team Scatter Radiation Exposure Using Mini C-Arm in a Simulated Forearm Fracture Fixation Model

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Abstract

Introduction: To our knowledge, no studies have studied the effect of metal instrumentation (MI) in the field of fluoroscopy regarding changes in the intensity, direction of scatter, and degree of radiation exposure to the patient and surgical team. The goal of this study was to determine whether the presence of MI increases scatter radiation exposure to the patient and surgical team when using a mini C-arm in the horizontal and vertical positions.

Methods: Four trials were conducted using a lamb limb specimen and a mini C-arm to simulate a forearm/wrist fracture fixation scenario. Radiation scatter percentages were measured with the mini C-arm in a vertical and horizontal position with and without the presence of MI (a six-hole 3.5-mm limited-contact dynamic compression plate attached to the specimen with six cortical screws and a self-retaining retractor) using a parallel plate radiation detector.

Results: The patient, scrub technician, circulating nurse, and anesthesiologist were exposed to no detectable radiation. In the horizontal position with the presence of MI, there was a 181-fold increase in scatter radiation exposure to the first assistant's eyes (0.016% versus 2.893%, 1.4×10^{-6} Sv/min versus 3.5×10^{-5} Sv/min) and increased exposure to the surgeon's hands compared with the horizontal position with no MI. In the vertical position, the scatter radiation received by the first assistant's eyes increased (zero versus 2.9×10^{-6} Sv/min) with MI present, whereas the only radiation measured for the surgeon was in the right hand which did not change with MI present (2.2×10^{-5} Sv/min).

Discussion: MI in the field of fluoroscopy increases scatter radiation exposure to a degree that may place the first assistant's yearly eye exposure in excess of the International Commission on Radiological Protection limit. Surgeons and their assistants should wear lead aprons, thyroid shields, and leaded glasses and minimize the usage of fluoroscopy with MI in the field.

The use of fluoroscopic imaging has become commonplace in an orthopaedic operating room. This has led to the invention and utility of the modern day mini C-arm. This device emits less radiation as compared to the larger conventional C-arm, is more cost-effective, and seldom requires a radiation technologist for operation.¹⁻³ The increased routine use of fluoroscopy in the operating room raises concern over the risk of radiation exposure and adverse effects to the patient and surgical staff. Effects of radiation can be broken down into two categories, stochastic and deterministic effects. The effects of acute, high-dose exposure of ionizing radiation have been well documented in the cases of Hiroshima and Nagasaki survivors and have been used as a guide to set limits on radiation exposure.⁴ However, little evidence has been produced to accurately assess the occupational health hazards of chronic low-dose radiation exposure. Recent evidence has suggested that orthopaedic surgeons are at a higher risk of developing malignancies as compared to the general public.⁵ However, there has never been a documented case of malignancy caused by chronic intraoperative radiation exposure. Orthopaedic surgical teams require increased knowledge of the exposure risk to staff and patients to reduce exposure to levels as low as reasonably achievable (as low as reasonably achievable [ALARA]). Radiosensitive tissues such as the thyroid gland, breast tissue, lens of the eyes, and gonads are of most concern in the setting of both acute and chronic ionizing radiation exposure.^{2,6} The lens of the eye is the most sensitive of these tissues to radiation exposure. New guide-

lines from the International Commission on Radiological Protection have recently reduced the yearly exposure limit by 7.5-fold (150 to 20 mSv/yr) because of the increased risk of developing radiation-associated lens damage.⁶

Radiation exposure from portable imaging devices has been studied in mini C-arm fluoroscopes, albeit not thoroughly and with conflicting results. It is often reported that mini C-arm fluoroscopy machines expose the surgical team to very little radiation outside of the direct beam when in use.^{1-3,7-10} Badman et al⁷ found the radiation exposure rates to be less with the mini C-arm compared with the conventional C-arm in various positions, distances, and durations of exposure. By contrast, Vosbikian et al¹¹ found the use of mini C-arm fluoroscopy doubled the amount of radiation to the surgeon's hands compared with when conventional C-arm fluoroscopy was used. In a study measuring the scatter radiation to the surgeon's eyes, thyroid, chest, groin, and index finger, Hoffler and Ilyas² did not find any notable difference in radiation between mini C-arm or conventional C-arm use. For both types of fluoroscopy machines, Hoffler and Ilyas² found the surgeon's hands received the most radiation exposure, with eyes receiving the second most. Athwal et al¹ found the radiation exposure to the surgeons and surgical room staff to be 5 to 10 times less than the conventional C-arm. In the relatively small amount of literature examining radiation scatter to the surgeon, a variety of conflicting results exist.

To our knowledge, no studies have been performed to compare the effect of the metal instrumentation (MI) (plates/screws/retractors) itself in the

field of fluoroscopy regarding changes in the intensity, direction of scatter, and degree of radiation exposure to the patient and the surgical team.^{1-3,10-13} Furthermore, there is limited literature describing the effects of changing the orientation of the mini C-arm from a horizontal to a vertical position on these same end points.¹ The goal of this study was to determine whether the presence of MI (plate, screws, and self-retaining retractor) increases the amount of scatter radiation exposure to the patient and surgical team when using the mini C-arm in the horizontal as opposed to the vertical position.

Methods

An InSight 2 Mini C-Arm (Hologic) was positioned over a hand table in a typical fashion for a forearm/wrist fracture fixation procedure. The machine was capable of producing a maximum output of 75 kVp and 100 μA and a spot size of 45 μm . The machine was set on the automatic setting, which auto-calculates the correct energy output to maximize the image quality. This setting was used because it mimics what is used in clinical practice. The direct beam radiation at each trial position is displayed in Table 1. The patient and surgical staff representing a circulating nurse, scrub technician, anesthesiologist, first assistant, and surgeon were positioned in a typical fashion as demonstrated in Figure 1. The distance from the center of the x-ray beam was measured and marked on the floor for each member's respective body region location (Table 2). All radiation exposure measurements were taken with a parallel plate radiation detector (Model 35050A electrometer;

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Keithley Instruments) in millirem per minute (mrem/min) with the detector hung from the ceiling above the previously marked positions to ensure there was no human exposure during the measurement process. The device was calibrated before the experiment. The measurements have been converted to Sieverts, which is an International System of Units measurement of ionizing radiation dose. Parallel plate radiation detectors have been shown to be accurate and reliable measures of x-ray dosimetry.^{13,14} Because of not being human subject research, the sponsoring institution's Institutional Review Board (IRB) deemed that the project was exempt from IRB approval.

The regions of the eyes, thyroid gland, chest, and gonads were measured for each member in the room and the surgeon's hands in relation to the specimen (Table 3). The study was conducted in four trials. Trial 1 was conducted with the mini C-arm placed in the horizontal plane, and the soft-tissue specimen (lamb limb) was positioned at the center of the x-ray beam. The image intensifier of the mini C-arm was positioned anterior to the surgeon's chest while the x-ray tube was directed at the surgeon (Figure 1). The mini C-arm direct beam intensity was measured at the level of the tissue specimen before each trial. The patient and staff members were then positioned from the center of the beam as outlined in Table 2. Continuous fluoroscopy was initiated until a constant measurement value was recorded by the Keithley electrometer at each of the defined anatomic regions (Figure 2). Trial 2 was conducted with the mini C-arm oriented in a vertical position with the x-ray tube beneath the hand table and pointed at the ceiling. The same subsequent steps were taken as described in the first trial. Trial 3 was conducted after placement of a six-hole limited-contact dynamic compression plate (Synthes), a stainless

Table 1
Direct Beam Radiation (Sv/min) Measured at the Surface of the Soft-tissue Specimen With the Mini C-Arm in Default Automatic Mode

Trial	Direct Beam Radiation (Sv/min)
Trial 1—horizontal without plate	8.93×10^{-3}
Trial 2—vertical without plate	2.73×10^{-3}
Trial 3—horizontal with plate	1.21×10^{-3}
Trial 4—vertical with plate	2.46×10^{-3}

Figure 1

Photograph showing typical positioning of the patient and staff during exposure. **A**, Surgeon, **(B)** scrub technician, **(C)** first assistant, **(D)** nurse, **(E)** anesthesiologist, and **(F)** patient.

steel plate measuring 3.5 mm on the anterior aspect of the lamb leg with six cortical screws (Figure 3). Trial 3 commenced with the mini C-arm oriented in the horizontal position in the same fashion as trial 1 with the plate, screws, and self-retaining retractor now present in the center of the imaging field of view. At our center, most fluoroscopy is used during fracture reduction and implant positioning. A self-retaining retractor was left in place to most closely recreate a commonly encountered imaging environment which includes using fluoroscopy with retractors, Weitlaner clamps, or other reduction clamps

present in the imaging field to maintain excellent fracture reduction. Trial 4 was conducted identically to trial 2 with the mini C-arm oriented in the vertical position with the addition of the plate, screws, and self-retaining retractor now present in the center of the imaging field of view.

Results

Direct beam radiation was measured at the surface of the soft-tissue specimen centered in the mini C-arm imaging field in each of the four trials to allow for radiation scatter percentage calculation [(scatter/direct beam) \times 100]

Table 2**Location of Measurement and Distance From the Center of Fluoroscopic Beam for Surgical Team Members**

Team Member	Eyes (cm)	Thyroid (cm)	Chest (cm)	Gonads (cm)	Hands (cm)
Surgeon	58 (54 from floor)	58 (50 from floor)	53	61	R: 11 L: 28
First assistant	74 (54 from floor)	74 (50 from floor)	69	61	N/A
Scrub technician	81	81	76	74	N/A
Patient	97	97	97	104	N/A
Anesthesiologist	244	244	244	244	N/A
Nurse	297	297	297	297	N/A

N/A = not applicable

Table 3**Direct Radiation Exposure Measurements, Trials 1 to 4 (Sv/min)**

Trial Staff	Eyes	Thyroid	Chest	Gonads	Hands
Trial 1-surgeon	0	0	4.9×10^{-6}	0	L: 2.2×10^{-6} R: 1.63×10^{-5}
Trial 1-first assistant	1.4×10^{-6}	3×10^{-6}	0	0	N/A
Trial 2-surgeon	0	0	0	0	L: 0 R: 2.2×10^{-5}
Trial 2-first assistant	0	0	7.6×10^{-6}	1.1×10^{-5}	N/A
Trial 3-surgeon	0	0	0	0	L: 2.2×10^{-5} R: 2.2×10^{-5}
Trial 3-first assistant	3.5×10^{-5}	0	0	0	N/A
Trial 4-surgeon	0	0	0	0	L: 0 R: 2.2×10^{-5}
Trial 4-first assistant	2.9×10^{-6}	0	6.3×10^{-6}	7×10^{-6}	N/A

N/A = not applicable

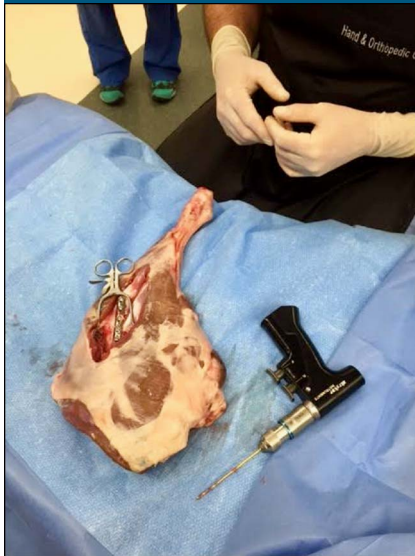
^aNo measurable direct radiation was detected for the circulating nurse, scrub technician, and anesthesiologist.**Figure 2**

Photograph depicting the mini C-arm in the horizontal position and scatter being measured in the region of the surgeon's eyes.

(Table 1). The radiation scatter percentage was calculated for the surgeon and first assistant to assess how both mini C-arm positioning and metal in the imaging field affect the radiation scatter (Table 4). No radiation scatter was detected at any of the other locations during the experiment (Figures 4,5). During trial 3 (horizontal position with MI), we measured a 66-fold increase in radiation scatter percentage compared with trial 1 (horizontal position with plain tissue specimen) to the surgeon's left hand (0.025% versus 1.653%, 2.2×10^{-6} Sv/min

versus 2.2×10^{-5} Sv/min), a 9-fold increase in radiation scatter percentage to the surgeon's right hand (0.182% versus 1.653%, 1.63×10^{-5} Sv/min versus 2.2×10^{-5} Sv/min), and a 181-fold increase in scatter percentage at the first assistant's eye level (0.016% versus 2.893%, 1.4×10^{-6} Sv/min versus 3.5×10^{-5} Sv/min) (Figure 4). During trial 4 (vertical position with MI), we measured a 1.4-fold decrease in radiation exposure to the first assistant's gonads compared with trial 2 (vertical position without MI) (0.285% versus 0.403%, 7×10^{-6}

Figure 3



Photograph demonstrating fixation of the six-hole 3.5-mm limited-contact dynamic compression plate (Synthes), which is a stainless steel plate.

versus 1.1×10^{-5} Sv/min) (Figure 5). In the vertical mini C-arm position, the presence of MI had minimal impact on the radiation scatter to the first assistant's chest (0.277% in trial 2 versus 0.257% in trial 4, 7.6×10^{-6} versus 6.3×10^{-6} Sv/min) but increased radiation to the first assistant's eyes (zero radiation in trial 2 versus 0.118% in trial 4, 0 versus 2.9×10^{-6} Sv/min). In the vertical mini C-arm position, the only place the surgeon was exposed to radiation was in the right hand, which was unchanged with or without the presence of MI (0.73% versus 0.815%, 2.2×10^{-5} Sv/min for both trials).

Discussion

Stochastic and deterministic theories are the main theories for describing the effect of ionizing radiation in the development of malignancies. Deterministic theory describes changes that lead to reproductive sterilization of cells, typically presenting as dermatological pathology.^{15,16}

Table 4

Measured Radiation Scatter Percentage [(Scatter/Direct Beam) \times 100] at Each Location for Trials 1 to 4

Trial Staff	Eyes	Thyroid	Chest	Gonads	Hands
Trial 1-surgeon	0	0	0.055	0	L: 0.025 R: 0.182
Trial 1-first assistant	0.016	0.034	0	0	N/A
Trial 2-surgeon	0	0	0	0	L: 0 R: 0.730
Trial 2-first assistant	0	0	0.277	0.403	N/A
Trial 3-surgeon	0	0	0	0	L: 1.653 R: 1.653
Trial 3-first assistant	2.893	0	0	0	N/A
Trial 4-surgeon	0	0	0	0	L: 0 R: 0.815
Trial 4-first assistant	0.118	0	0.257	0.285	N/A

N/A = not applicable

^aNo measurable scatter radiation was detected for the circulating nurse, scrub technician, and anesthesiologist.

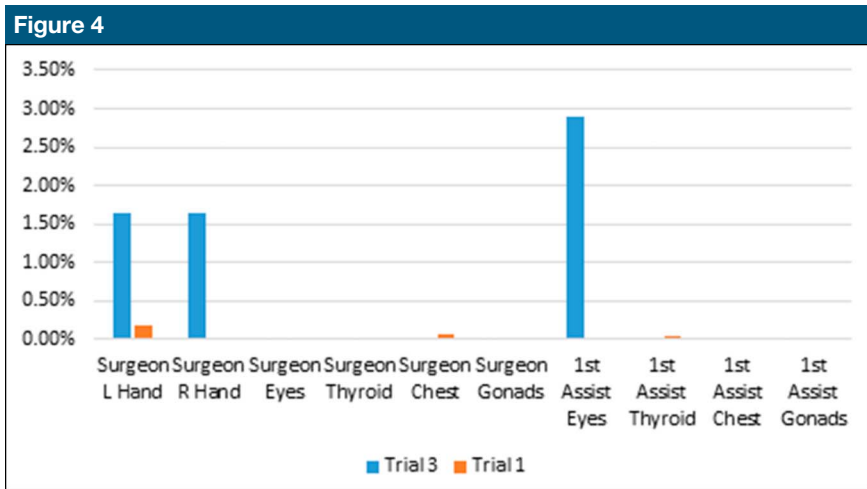
Stochastic theory describes irreversible cumulative changes to DNA that lead to malignancy. These can be created during an acute exposure to a large amount of radiation, such as Hiroshima, or small chronic exposures overtime, such as with long-term exposure to x-rays.^{11,15} It is important that any medical staff exposed to ionizing radiation reduce exposure to decrease the risk of pathology due to stochastic and deterministic effects.

When using fluoroscopy during a given operation, surgical staff and the patient may be exposed to either direct or scatter radiation. Scatter radiation occurs when the x-ray beams are deflected off their initial path when coming in contact with a surface such as the patient or surgical instruments and equipment. Giordano et al¹⁰ tested scatter on a phantom limb and showed minimal scatter associated with various positions of the phantom limb with the mini C-arm in the vertical position. Wang et al¹⁷ found that radiation at the level of the surgeon's eyes was below the acceptable limit for both mini and standard C-arm. This supports our

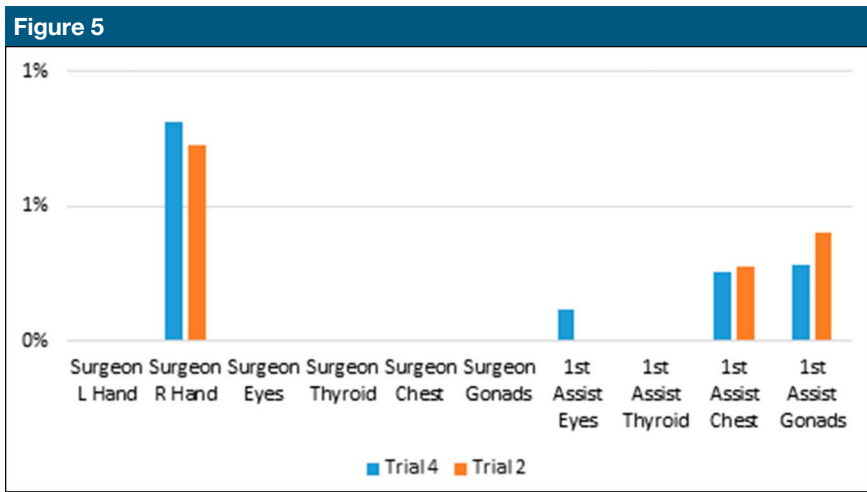
findings of no notable radiation detected at the level of the surgeon's eyes.

To our knowledge, there are only two studies testing the effect on scatter radiation with MI in the surgical field.^{1,17} We think we are the first to examine the magnitude of the radiation exposure that the first assistant is exposed to from the mini C-arm.

Our data demonstrated the most notable exposure to scatter radiation when the mini C-arm was in the horizontal position, causing the scatter to be directed toward the surgeon's hands (1.653% for both hands) and the first assistant's eyes (2.893%), both while seated, with MI on the field. Chapman et al¹⁸ also found the greatest degree of radiation to the surgeon's hands to occur when the mini C-arm was in the horizontal position. Tasbas et al¹⁹ found the first assistant's head, neck, and eyes to have the greatest radiation exposure from the standard C-arm compared with other body regions of the first assistant and lead surgeon. Although the study of Tasbas¹⁹ was with a standard C-arm, the same principle of radiation exposure was affected by the



Graph comparing scatter percentage with the mini C-arm in the horizontal position without metal instrumentation (MI) (trial 1) and with MI (trial 3).



Graph comparing scatter percentage with the mini C-arm in the vertical position without metal instrumentation (MI) (trial 2) and with MI (trial 4).

magnitude of scatter and distance from the energy source applied.

In the vertical mini C-arm position, we also noted scatter directed at the first assistant’s gonads (with the plate: 0.285% and without the plate: 0.403%, 7×10^{-6} versus 1.1×10^{-5} Sv/min, respectively) and chest (with the plate: 0.257% and without the plate: 0.277%, 6.3×10^{-6} versus 7.6×10^{-6} Sv/min). The decrease in radiation to the first assistant’s chest and gonads with MI present could be

attributed to increased directional radiation scatter toward the x-ray tube and into the floor. The MI may have altered the dynamics of the radiation scatter. Because there was no clinical significance to measuring the radiation scatter at the floor, we do not have this measurement.

A study by Singer⁸ determined that the average fluoroscopy time per case among hand surgeons was 51 ± 36.9 seconds. When extrapolating

these data using an average of 5 cases per week over the course of 46 weeks with the average of our direct beam radiation (0.00384 Sv/min), it was determined that the surgeon’s hands would receive an average yearly exposure of 0.0127 Sv (range: 0.00343 to 0.0214 Sv) and the first assistant’s eyes would receive an average of 0.0224 Sv per year (range: 0.006 to 0.0386 Sv/yr) from scatter radiation alone with the mini C-arm in the horizontal position and the subjects in the seated position. Using our data and the time data of Singers⁸, it would take ~175 minutes of fluoroscopy exposure to the first assistant’s eyes with the mini C-arm to reach the recommended limit of 0.02 Sv/yr suggested by the ICRP for eye exposure.⁶ It would take ~437 minutes of fluoroscopy time to reach the absolute limit of 0.05 Sv/yr for eye exposure.⁶ Vano et al²⁰ discovered posterior capsular opacification in cardiac catheterization laboratory members exposed to a cumulative 0.1 to 18.9 Sv. It would take less than 5 years for changes to be seen using our numbers based on minimum numbers in the range Vano et al²⁰ found. When looking at a female first assistant standing, the breast height would be in the proximity of the eyes of a seated first assistant. Even with ~437 minutes of fluoroscopy, 0.05 Sv/yr is below the recommendation of receiving less than 0.15 Sv/yr to organs.²¹

Limitations of this study include the use of only one type of plate, two distinct angles of the mini C-arm, testing with the first assistant seated, only running two trials per position, and not having comparison trials of only the plate and screws in place with no retractor present. We used a standard 3.5-mm limited-contact dynamic compression plate to simulate the typical setup for a forearm fracture/fixation repair. It may have been beneficial to test differing lengths, thickness,

component makeup (stainless steel versus titanium), and implants to see whether these changes would alter the scatter intensity. Second, we only tested two distinct angles of the mini C-arm. Although the vertical and horizontal positions are used frequently, it would be beneficial to measure the change of scatter throughout the entire 180° range of the machine. Different oblique angles are often needed to achieve the best visualization of the surgical anatomy. Furthermore, another limitation was only testing the first assistant and surgeon in seated positions. More study is needed to look at the scatter at the eyes and thyroid of the surgeon and first assistant while standing. Athwal¹ suggested that the safest position was to stand behind the image intensifier. Following this principle would have effectively lowered the scatter that we measured for the first assistant, who was behind the x-ray tube.

In the vertical mini C-arm position, the x-ray tube was placed underneath the hand table to follow the findings of Athwal¹ on the safest C-arm positioning. However, in real operative circumstances, some surgeons may prefer to use the x-ray tube above the table with the patient's limb resting on the image intensifier above the table. We previously described increased directional radiation scatter toward the x-ray tube when MI was present in the vertical mini C-arm position. Thus, using the x-ray tube above the hand table may cause more radiation scatter toward the surgeon's and first assistant's chest, hands, and eyes.

Last, running more than two trials could have contributed to a better understanding of the true average of scatter from the two positions. We acknowledge the presence of a retractor in the imaging field confounds identification of whether radiation scatter is due to the retractor

or orthopaedic implant or a combination of such factors.

The goal of our study was to determine the effect that metal in the imaging field had on scatter radiation from a mini C-arm in the vertical and horizontal positions. We found increased scatter toward the first assistant's gonads and chest and the surgeon's right hand in the vertical position without metal in the field compared with the horizontal position without metal. Furthermore, we found that the region of the first assistant's eyes and the surgeon's left and right hands were exposed to increased scatter radiation in the horizontal position on placement of metal in the imaging field. Most markedly, the first assistant's eye region was exposed to radiation that would exceed the recommended 0.02 Sv/yr suggested by the ICRP⁶ with the mini C-arm in the horizontal position. It is with this knowledge that we advise lead aprons and thyroid shields be worn when using ionizing radiation in the operating room. Given the results of our study and the new guidelines by the ICRP⁶ for eye exposure limits, we recommend that anyone working in the surgical field wear lead glasses to decrease eye exposure to the radiation. We would also recommend using the mini C-arm in the vertical position as much as possible to help prevent scatter exposure to the sensitive tissue of the lens. Last, we recommend minimizing the amount of fluoroscopy used when retractors, fracture reduction clamps, or other instruments used to aid in reduction are present in the imaging field.

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