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Exposure to Direct and Scatter Radiation with Use of Mini-C-Arm Fluoroscopy

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Background: Mini-c-arm fluoroscopy has become an important resource to the orthopaedic surgeon. Exposure of the orthopaedic surgical team to radiation during standard large-c-arm fluoroscopy has been well studied; however, little is known about the amount of exposure to which a surgical team is subjected with the use of mini-c-arm fluoroscopy. Moreover, there is controversy regarding the use of protective measures with mini-c-arm fluoroscopy.

Methods: We evaluated the use of mini-c-arm fluoroscopy during a simulated surgical procedure to quantify the relative radiation doses at various locations in the operative field. A standard calibrated mini-c-arm fluoroscope was used to image a phantom upper extremity with thirteen radiation dosimeters placed at various distances and angulations to detect radiation exposure.

Results: After 155 sequential fluoroscopy exposures, totaling 300.2 seconds of imaging time, only the sensor placed in a direct line with the imaging beam recorded a substantial amount of measurable radiation exposure.

Conclusions: The surgical team is exposed to minimal radiation during routine use of mini-c-arm fluoroscopy, except when they are in the direct path of the radiation beam.

Over the past several decades, mobile fluoroscopy has contributed greatly toward making procedures less invasive and less costly, which has helped facilitate quicker recovery and reduce inpatient hospital time. Initially, fluoroscopy was used during only selected orthopaedic procedures such as intramedullary femoral nailing. Now, nearly every medical discipline has adopted the routine use of fluoroscopy to meet its various needs. The use of fluoroscopic imaging to guide fracture reduction and facilitate anatomic localization of implant placement has become indispensable to surgeons attempting to achieve a radiographically optimal result.

As physicians and technologists become more skilled with fluoroscopic interventions, the surgical procedures themselves continue to evolve and increase in complexity, sometimes requiring fluoroscopy times in excess of one hour per procedure[1,2]. This places those in proximity to the radiation beam at an increased risk for radiation exposure. The use of mini-c-arm fluoroscopy has gained popularity in recent years for a number of reasons. In addition to its ability to produce quality images with use of considerably less radiation than is used by a standard large c-arm, the increased mobility and ease of use of the mini c-arm have made its presence commonplace in the emergency department, the operating room, and the outpatient clinic. During selected orthopaedic procedures done with standard-c-arm fluoroscopy, the patients' measured radiation exposure was found[3] to range from 1200 to 4000 mrem/min. In contrast, dose ranges of 120 to 400 mrem/min have been reported with the use of a mini-c-arm unit[4]. From a fiscal standpoint, the mini c-arm is less costly to the institution that purchases and maintains the unit. In many instances, routine use of a mini c-arm does not require the assistance of a radiology technician, making its use quite cost effective.

Certainly, standard-c-arm fluoroscopy produces images that are of higher quality than the images produced by its mini-c-arm counterpart, and the standard c-arm may be used to image many of the same body parts as can be imaged with

the mini-c-arm unit. However, applications for imaging with the mini c-arm unit are different from those for imaging with a large c-arm and are not interchangeable. This fact underscores the importance of appropriate and judicious use of the mini-c-arm unit for its intended indications.

The biologic effects of radiation have been shown to damage human DNA and the cellular structural matrix, potentially causing genetic alterations that could result in malignant changes[5]. In addition, skin burns, dermatitis, and cataract formation have been reported to occur as the result of radiation exposure[6]. The National Council on Radiation Protection and Measurements recommends an annual exposure dose limit in areas adjacent to x-ray rooms of no more than 5 rem (5000 mrem) for occupational workers and 0.1 rem (100 mrem) for persons in uncontrolled areas[7]. The International Commission on Radiological Protection recom-

mends an annual whole-body dose limit of 2 rem (2000 mrem). Furthermore, recommended annual dose limits for children, fetuses, human embryos, and specific body areas have been reported[8-10].

Previous studies on the use of intraoperative fluoroscopy during selected orthopaedic procedures have focused on various factors that can be altered to reduce the amount of radiation to which the patient and surgical team are subjected. These include minimizing exposure time, reducing exposure factors, manipulating the x-ray beam with collimation, orienting the fluoroscopic beam in an inverted position relative to the patient, strategic positioning of the surgeon within the operative field, judicious use of protective shielding during imaging, and maximizing the distance of the surgeon from the radiation beam[3,10-13]. However, in some cases, it is not possible for the surgeon to distance him or herself from the radiation beam, espe-
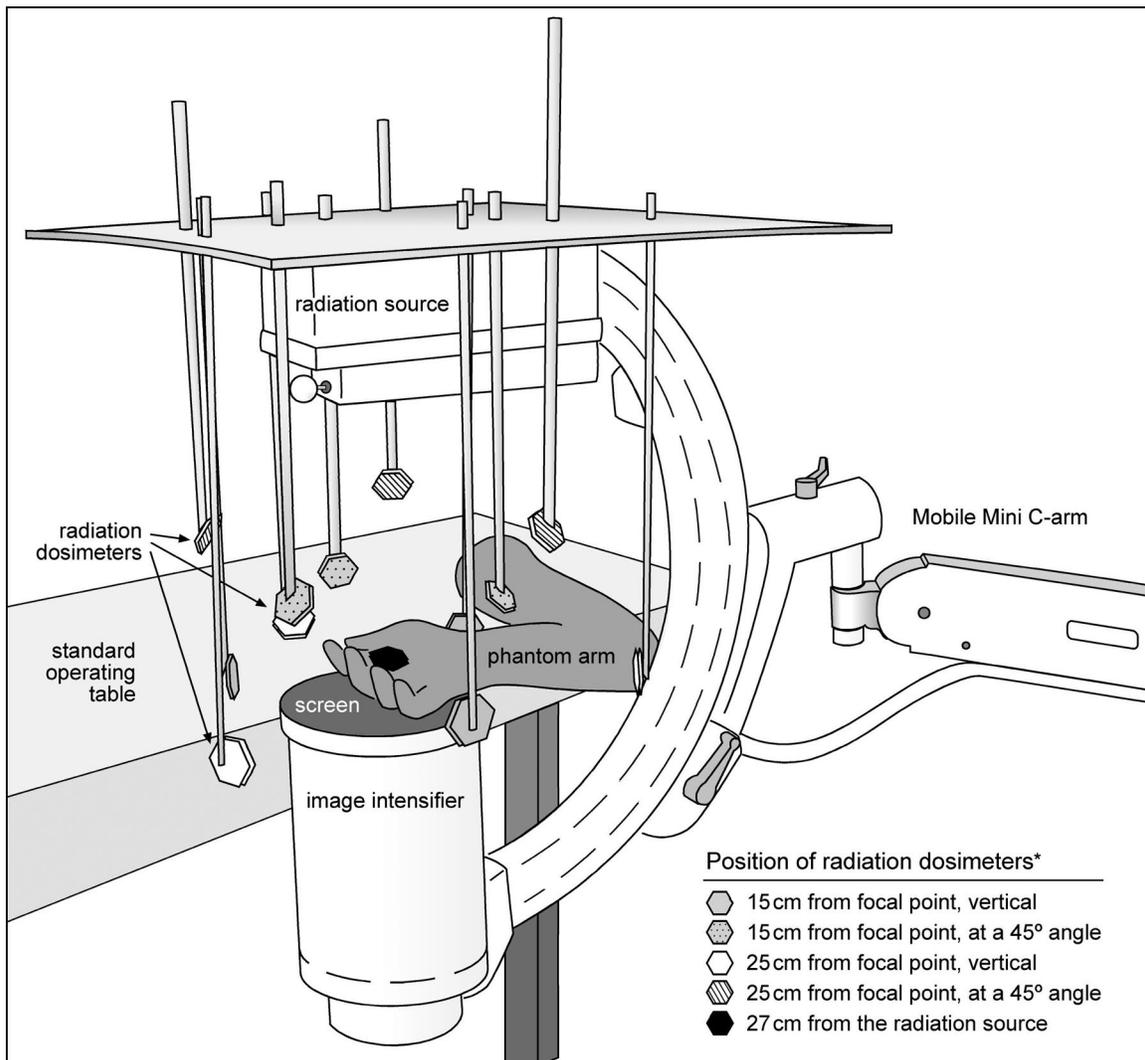

Fig. 1

Experimental setup and sensor positioning. *These dosimeters were placed at each position, except 27 cm from the radiation source, where one dosimeter was positioned.

TABLE I Recorded Exposure of a Phantom Limb as Measured by Thirteen Radiation Dosimeters Placed at Various Distances and Angles Relative to a Focal Point on the Image-Intensifier Screen			
	Exposure *(mrem)*		
Sensor Placement	Deep	Eye	Shallow
On phantom hand (27 cm from source) (#1)	181	181	272
15 cm on horizontal			
#2	2	2	2
#3	<1	<1	<1
#4	<1	<1	<1
25 cm on horizontal			
#5	<1	<1	<1
#6	<1	<1	<1
#7	<1	<1	<1
15 cm at 45°			
#8	<1	<1	<1
#9	2	3	3
#10	<1	2	2
25 cm at 45°			
#11	<1	1	1
#12	<1	<1	<1
#13	<1	<1	<1

cially when maintaining a difficult fracture reduction is crucial to achieving a successful outcome. Other measures for reducing the radiation dose may be impractical as a result of technical limitations associated with various procedures.

The exposure of the orthopaedic surgical team to radiation during the use of standard large-c-arm fluoroscopy has been well studied and has been reported for a wide variety of orthopaedic procedures[10,12-16]. However, little is known about the amount of radiation exposure to which a surgical team is subjected when a mini-c-arm unit is used. Many surgeons assume that using a mini-c-arm unit obviates the need for protective shielding or the use of other precautions recommended for standard inverted-c-arm fluoroscopy[17]. These assumptions exist despite the fact that, during mini-c-arm fluoroscopy, the surgeon must frequently position himself or herself in close proximity to the radiation beam, an often ignored disadvantage associated with use of a mini c-arm. Here, we report on the use of mini-c-arm fluoroscopy and the relative radiation exposure to which the orthopaedic operating team is subjected during a simulated surgical procedure.

Materials and Methods

Instrumentation

A calibrated OEC MINI6600 Mobile Digital C-Arm (OEC Medical Systems, Salt Lake City, Utah) was placed adjacent to a standard operating table in an operating theater. The OEC MINI6600 image intensifier has a diameter of 15.2 cm and is capable of producing a maximum output power of 7.5 W at 75 kV and 100 μÅ. An anthropomorphic phantom upper extremity, composed of cadaver bone surrounded by tissue-sensitive material (with the percentage of body fat and the bone mineral density equal to those of human tissue), was positioned with the humerus on the operating table and the hand resting on the image intensifier (Fig. 1). With this experimental setup, we attempted to accurately reproduce the position of a patient during a standard hand or wrist examination.

Sensors

To detect radiation exposure, thirteen radiation dosimeters were positioned at various distances and angles relative to a focal point on the image intensifier. Six of the sensors were positioned at an angle of 45° relative to the direction of the radiation beam. The Luxel luminescence dosimeter (Landauer, Glenwood, Illinois) measures radiation exposure through a layer of aluminum oxide and detects energies from 5 keV to in excess of 40 MeV[18]. The dosimeter can be restimulated numerous times to confirm the accuracy of a radiation dose measurement and is precise to ±1 mrem. The exposure range is from 1 to 1000 mrem for x-radiation and gamma radiation. Dose equivalents from exposure consist of deep, eye, and shallow values reported in mrem.

Sensor Positioning

As noted by Badman et al., positioning of the limb directly on the image intensifier rather than midway between the radiation source and the image intensifier can reduce the radiation dose[4]. One sensor was positioned in the palm of the phantom hand, 27 cm from the x-ray-beam source. The phantom hand was rested directly on the screen of the image intensifier. Three sensors were each placed in a vertical position, 15 cm

from a horizontal point on the image intensifier, and three were positioned 15 cm from the same focal point at an angle of 45°. In addition, three sensors were each placed 25 cm from the same focal point in the horizontal plane, and three were placed 25 cm from the focal point at an angle of 45° (Fig. 1). One sensor was placed in the hallway, 15 ft (4.6 m) away from the focal point, to serve as a control. With this experimental setup, we attempted to reproduce realistic surgeon and assistant positioning with attention paid not only to the distance from the radiation beam, but also to the angulation, as persons in the operating field may be exposed to both direct radiation and reflected radiation (scatter).

Testing Procedure

Our test included 155 sequential fluoroscopy images. The fluoroscopic technique factors (57 kVp and 38 μÅ) were adjusted automatically in the normal mode on the mini-c-arm unit. The total fluoroscopy time was 300.2 seconds.

Results

The total radiation captured from each of the thirteen radiation dosimeters is recorded in Table I. Only the sensor placed in direct line with the imaging beam recorded a substantial amount of radiation exposure over the course of the fluoroscopy time.

Discussion

During an operation performed with fluoroscopy, the patient and surgical team are exposed to radiation in the form of either direct radiation or scatter. When a member of the surgical team inadvertently crosses the path between the radiation generator and the image intensifier while the c-arm is active, he or she is subject to direct radiation. Scatter is produced through the interaction between the primary x-ray beam and objects in its path such as human tissue, the operating room table, and nearby surgical instruments. In a study on exposure of hand surgeons to radiation during the use of intraoperative mini-c-arm fluoroscopy, Singer found that surgeons' hands were exposed to an average of 20 ± 12.3 mrem/case (range, 5 to 80 mrem/case) and that the surgeons used an average of 51 ± 36.9 sec/case of fluoroscopy time; the radiation exposure was higher than would be predicted[19]. In that study, five hand surgeons used a total of eighty-one thermoluminescent ring dosimeters to measure exposure to their hands during surgery on the finger, hand, or wrist. Scatter data were also collected with use of an anthropomorphic wrist phantom and radiation dosimeters arranged at varying distances from a central focal point on the image intensifier. Singer found no correlation between fluoroscopy time and the total amount of radiation exposure recorded by each surgeon but did note that, beyond the radius of the image intensifier, the amount of radiation from scatter fell sharply. He postulated that, because hand surgeons are often required to work in close proximity to the mini-c-arm beam, they may inadvertently subject themselves to a substantial level of direct beam radiation in addition to the unavoidable exposure produced from scatter. The

dosimeter readings in our study also indicated that the surgeon, patient, and operating staff are subjected to minimal radiation exposure from scatter beyond the direct path of the radiation beam. This finding supports the notion that, in Singer's study, the exposure of each surgeon resulted from inadvertent contact with the direct beam, due to close surgeon positioning, rather than from scatter.

The radiation exposure to which the primary surgeon and operating team are subjected during the use of standard large-c-arm fluoroscopy has been well studied and documented for a wide assortment of procedures performed under a variety of clinical scenarios[4,10-16]. However, we are aware of only a handful of studies in which radiation exposure associated with mini-c-arm fluoroscopy was evaluated under regular working conditions[4,10,19]. Furthermore, to our knowledge, none of those studies involved concurrent use of multiple dosimeter sensors placed at different distances and angles from a focal point in an effort to accurately capture both direct radiation and reflected radiation (scatter) from the phantom limb. Our study supports the established principle that the rate of radiation exposure drops precipitously beyond the path of the radiation beam and strengthens the notion that direct contact with the radiation beam can result in substantial exposure. As would be predicted, exposure was found to be greatest at the sensor positioned directly in the palm of the phantom limb (deep and eye exposure of 181 mrem and shallow exposure of 272 mrem; data based on five-minute total exposure time). Our analysis indicated that a surgeon would exceed the annual radiation dose limit after approximately ninety-two minutes of direct beam exposure. Avoidance of direct beam exposure during the use of mobile fluoroscopy is already a well-established safety guideline; therefore, adherence to established safety principles should ensure a subthreshold annual exposure rate. Our study suggests that, in a clinical situation where a mini-c-arm fluoroscopy unit is used and the extremity to be imaged is rested directly on the image intensifier, the surgeon, operating staff, and patient are exposed to minimal radiation when they are positioned beyond 15 cm from the point of focus on the image intensifier.

One limitation of this study is that we used a phantom limb that was placed on the image-intensifier screen rather than utilizing a formal operating-table setup. We thought that, since the limb to be examined is often positioned directly on the image intensifier during a hand or wrist procedure and is less commonly positioned in this manner during a foot or ankle procedure, our setup would mimic a true operating-room situation. In addition, as noted by Badman et al., the phantom extremity is exposed to less radiation when it is rested on the image-intensifier screen than when it is positioned midway between the radiation source and the image-intensifier screen[4]. Moreover, in a foot or hand procedure, the limb is sometimes rested on the image intensifier to enlarge the field of view. Alteration of radiation dosage in the form of scatter has been studied in a variety of experimental setups, and information regarding scatter data is available in the OEC MINI6600 Operator's Guide[20]. As Singer indicated, limb posi-

tioning has a consequential effect on the amount of exposure to direct and scatter radiation produced by imaging with a mini-c-arm unit[21]. In our experimental setup, we did not alter the distance from the radiation source to the phantom limb because our goal was to establish radiation exposure data using what we thought was a realistic operating-room setting.

A second limitation of our study is that we examined radiation exposure resulting from use of only a single mini-c-arm fluoroscopy unit rather than incorporating data from a variety of mini-c-arm units. Although each mini-c-arm fluoroscope is calibrated regularly to meet institution standards, radiation exposure may nonetheless vary from unit to unit and pose different exposure risks based on subtle variations in the radiation produced.

In summary, mini-c-arm fluoroscopy remains a valuable resource to the orthopaedic surgeon. Our data indicate that individuals outside the path of the radiation beam, including the surgeon, assistants, observers, and patient, are exposed to minimal radiation. However, all identifiable measures should still be taken to avoid unnecessary exposure, particularly prolonged exposure to direct beam radiation, as frequently as possible. The mini-c-arm operator should continue to use protective measures, and appropriate imaging indications should continue to be followed, as the cumulative non-stochastic effects of exposure to trace radiation dosages remain unknown. ∎

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