TITLE: Dose Reconstruction for Physician A

SCOPE: Radiation Safety Office

PURPOSE: To evaluate exposures from clinical work performed by Physician A to ensure his dose for calendar year 2021 and 2022 did not exceed limits set forth by the Nuclear Regulatory Commission.

Introduction
It has come to our attention that Physician A has not properly worn his Dosimeter for Interventional Radiology procedures for several months during Calendar Years 2021 and 2022. We have developed a methodology to estimate his doses to ensure his health and safety as well as to evaluate any exposures beyond the regulatory limits set forth by the Nuclear Regulatory Commission (NRC).

Methodology
A review of Dosimetry records for the past 2 calendar years showed that Physician A has only worn his Dosimeter for 5 of the 24 months. We have confirmed that he has performed various IR procedures for each of the preceding 24 months but only 5 of the months have readings beyond background. The readings obtained during the 5 months were consistent with expected values as well as values in the published literature.

The amount of fluoroscopy time associated for Physician A was obtained and summarized in Table 1 (see below).

Period	Time (Seconds)	Time (Minutes)
Jan - 2021	8,219	137
Feb - 2021	2,580	43
Mar - 2021	5,176	86
Apr - 2021	5,799	97
May - 2021	5,646	94
Jun - 2021	4,147	69
Jul - 2021	4,557	76
Aug - 2021	8,993	150
Sep - 2021	5,742	96
Oct - 2021	7,024	117
Nov - 2021	3,812	64
Dec - 2021	10,435	174

Period	Time (Seconds)	Time (Minutes)
Jan - 2022	10,558	176
Feb - 2022	6,944	116
Mar - 2022	17,130	286
Apr - 2022	14,969	249
May - 2022	2,863	48
Jun - 2022	7,494	125
Jul - 2022	5,697	95
Aug - 2022	6,294	105
Sep - 2022	5,017	84
Oct - 2022	3,845	64
Nov - 2022	8,898	148
Dec - 2022	3,617	60

Table 1: *Fluoroscopy Times by Month for Physician A.*

Badge Readings for the months of September 2021 – December 2021 and November 2022 were compared to Fluoroscopy Beam-On Time. The results showed an exposure range from 2.3 to 6.2 mR/minute.

Period	Time (Seconds)	Time (Minutes)	Badge Readings (mR)	Corresponding Exposure Rate (mR/minute)
Sep - 2021	5,742	95.7	589	6.2
Oct - 2021	7,024	117.1	275	2.3
Nov - 2021	3,812	63.5	243	3.8
Dec - 2021	10,435	173.9	529	3.0
Nov - 2022	8,898	148.3	464	3.1

Table 2: *Correlation of Fluoroscopy time and Dosimeter Readings with associated Exposure Rates.*

A literature search was performed in an attempt to validate that the exposure rate readings were consistent with peer institutions. Specifically the American Journal of Roentgenology, *Radiation Protection for the Fluoroscopy Operator and Staff*, June 1, 2026, AJR2016; 207:745-754.

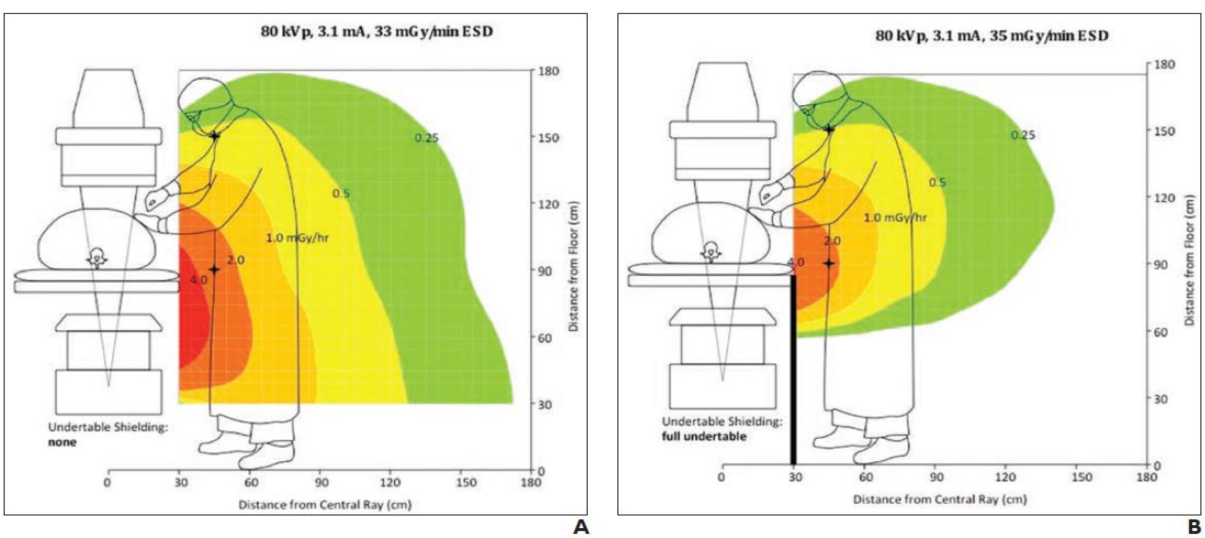

Fig. 1—Scatter radiation distribution as function of distance with undertable x-ray tube system. ESD = entrance skin dose rate.
A and **B**, Schematics and graphs show results without (**A**) and with (**B**) table skirt. (Reproduced with permission from [16])

This paper indicates that the exposure rates for an operator with and without a table skirt are approximately 3.0 mR/min and 6.0 mR/min, respectively (See Figure 1 above). Utilizing the information described in this paper was preferred to onsite measurements due to the inherent uncertainty in position of the physician relative to the source.

Knowing the fluoroscopy time, we calculated the expected exposure based on the bounding conditions set above. In most cases, the doses correlate very well with the expected doses based on a unit with a table skirt, 3 mR/hr. See the results in Table 3 (see below).

Period	Time (Seconds)	Time (Minutes)	Badge Readings (mR)	Corresponding Exposure Rate (mR/minute)	Estimate Dose per Month (mR)	
					3 mR/minute	6 mR/minute
Sep - 2021	5,742	95.7	589	6.2	287	574
Oct - 2021	7,024	117.1	275	2.3	351	702
Nov - 2021	3,812	63.5	243	3.8	191	381
Dec - 2021	10,435	173.9	529	3.0	522	1044
Nov - 2022	8,898	148.3	464	3.1	445	890

Table 3: *Estimated to based-on fluoroscopy time.*

This methodology was applied to all months in calendar years 2021 and 2022. We have confirmed with Physician A that he has worn lead for all procedures. As a result, we are able to reduce the estimated dose by 70%. The results are detailed in Table 4 (see below).

Period	Time (Seconds)	Time (Minutes)	Badge Readings (mR)	Corresponding Exposure Rate (mR/minute)	Estimate Dose per Month (mR)	
					3 mR/minute	6 mR/minute
Jan - 2021	8219	137.0			411	822
Feb - 2021	2580	43.0			129	258
Mar - 2021	5176	86.3			259	518
Apr - 2021	5799	96.7			290	580
May - 2021	5646	94.1			282	565
Jun - 2021	4147	69.1			207	415
Jul - 2021	4557	76.0			228	456
Aug - 2021	8993	149.9			450	899
Sep - 2021	5742	95.7	589	6.2	287	574
Oct - 2021	7024	117.1	275	2.3	351	702
Nov - 2021	3812	63.5	243	3.8	191	381
Dec - 2021	10435	173.9	529	3.0	522	1044
TOTAL FOR 2021 (Uncorrected)					3607	7213
TOTAL FOR 2021 (Corrected for Lead)					1082	2164

Period	Time (Seconds)	Time (Minutes)	Badge Readings (mR)	Corresponding Exposure Rate (mR/minute)	Estimate Dose per Month (mR)	
					3 mR/minute	6 mR/minute
Jan - 2022	10558	176.0			528	1056
Feb - 2022	6944	115.7			347	694
Mar - 2022	17130	285.5			857	1713
Apr - 2022	14969	249.5			748	1497
May - 2022	2863	47.7			143	286
Jun - 2022	7494	124.9			375	749
Jul - 2022	5697	95.0			285	570
Aug - 2022	6294	104.9			315	629
Sep - 2022	5017	83.6			251	502
Oct - 2022	3845	64.1			192	385
Nov - 2022	8898	148.3	464	3.1	445	890
Dec - 2022	3617	60.3			181	362
TOTAL FOR 2022 (Uncorrected)					4138	8277
TOTAL FOR 2022 (Corrected for Lead)					1242	2483

Table 4: *Estimated exposure based on Fluoroscopy time for varying exposure rates.*

In summary, Physician A reasonably received between 1,082 and 2,164 mRem for 2021 and between 1,242 and 2,483 mRem for 2022. These values represent less than half of the regulatory limits set forth by the NRC for occupational exposure. We feel confident that his annual exposures did not reasonable come close to exceeding NRC limits.

In addition to these calculations, the Radiation Safety will issue Physician A an additional dosimeter and ensure complete compliance with its proper use for all cases for a period of 8 weeks. These results will be compared to the calculations utilizing the methodology described herein as an independent validation for estimating total exposure based on expected dose rate and total fluoroscopy time.

Vascular and Interventional Radiology • Review

AJR FOCUS ON:

Radiation Protection for the Fluoroscopy Operator and Staff

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OBJECTIVE. The purposes of this article are to review available data regarding the range of protection devices and garments with a focus on eye protection and to summarize techniques for reducing scatter radiation exposure.

CONCLUSION. Fluoroscopy operators and staff can greatly reduce their radiation exposure by wearing properly fitted protective garments, positioning protective devices to block scatter radiation, and adhering to good radiation practices. By understanding the essentials of radiation physics, protective equipment, and the features of each imaging system, operators and staff can capitalize on opportunities for radiation protection while minimizing ergonomic strain. Practicing and promoting a culture of radiation safety can help fluoroscopy operators and staff enjoy long, productive careers helping patients.

Articles investigating a potential association between occupational exposure to radiation and brain tumors and other cancers have reinvigorated interventionalists' interest in radiation protection [1–6]. Unlike those in the era of early medical use of radiation, physicians now have a much healthier respect for the potential risks. In 1990, the as-low-as-reasonably achievable principle was established to encourage physicians to limit the use of radiation to only that needed without compromising patient care [7]. The literature continues to raise awareness of radiation risks and protection, encouraging dose reduction to the patient and the operator [4, 6]. Meanwhile, more physicians outside the field of radiology are also practicing fluoroscopic procedures [8, 9], typically without the same level of training in physics and radiation safety required of radiologists [10].

Nevertheless, many interventionalists remain perfunctory in their radiation safety practices. In 1993, Niklason and colleagues [11] found that most operators (70%) never wore protective glasses and that only 10% wore them consistently. Approximately one-fourth of operators (27%) never wore thyroid shields and less than one-half (47%) wore them consistently. A more recent study [12] showed that the use of personal radiation protective devices improved from a level suggesting nonchalance to a more consistent level. Specifically, the use of lead glasses increased from 10% to 54% and the use of a thyroid shield increased from 47% to 94% over 2 decades [11, 12]. In the 1993 study by Niklason et al., nearly one-half of fluoroscopy operators (43%) never wore radiation dosimeters. A 2006 study of a cohort of interventional cardiologists [13] showed that as many as 30% did not submit their dosimeters for processing. Although this proportion decreased to 10% by 2013, still only 40% wore dosimeters regularly [14]. Inconsistent dosimeter monitoring leads to underestimation of radiation exposure of personnel and could propagate complacency regarding radiation protection. These study results show that there is still room for improvement in the consistent and proper use of protective equipment and dosimeters.

Not all facilities provide adequate radiation protection garments for health workers. A 2014 study in which the availability of appropriate sizes of protective aprons at 14 hospitals was evaluated [15] showed that three hospitals did not have enough protective aprons and that a range of sizes was not always available, 72% of aprons being in sizes medium and large. Only one hospital paid for individualized radiation aprons. Use of poorly fitted garments can lead to unnecessary radiation exposure to the operator by leaving important areas exposed.

Keywords: cataracts, dose estimation, fluoroscopy, interventional radiology, quality improvement, radiation biology, radiation dose, radiation protection, radiation risk

DOI:10.2214/AJR.16.16556

Received April 6, 2016; accepted after revision June 1, 2016.

M. P. Andre received ultrasound research grants from Siemens Medical Solutions and GE Healthcare.
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AJR 2016; 207:745–754

0361–803X/16/2074–745

This review focuses on radiation protection. We present the available evidence regarding radiation protection devices and summarize techniques for reducing radiation exposure to the operators and staff. We intend to use this opportunity to empower readers with sound radiation safety guidelines to protect themselves, staff, and trainees.

Radiation Shields

Mobile and Fixed Shielding

Fluoroscopy suites are equipped with a variety of shields for personnel, including table skirts, ceiling-suspended shielding, and mobile shields on wheels. These shields decrease scatter radiation from the patient, which constitutes the main source of operator exposure (Fig. 1). Table skirts attach to either side of the patient couch and provide significant scatter reduction to the operator from under the table [16] (Figs. 1B and 2B) with a 64% reduction in extremity doses [17]. Anticipation of the positional requirements for each procedure and areas of greatest scatter can determine the optimal positioning of table skirts before sterile preparation.

When positioned close to the patient's skin, ceiling-suspended shields (Fig. 2A) can reduce scattered radiation to the operator's head, neck, and lens by 50–60% [18] and as much as 90–98%, depending on the location of the x-ray source [19–21]. Positioning these shields, however, can be awkward in some procedures and impossible in others because of how the shields are mounted. Even so, technologists can promote a culture of radiation safety by routinely preparing the ceiling-suspended shields, because they offer protection for both the operator and adjacent staff.

Mobile shields (Fig. 2C) of 0.5-mm lead equivalence can attenuate 95% of scatter radiation in the anteroposterior projection and 70% in the lateral projection [20]. A mobile shield combined with a nondisposable 1-mm lead equivalent patient apron (outside the primary beam) attenuates 98% of scatter. Mobile shields can protect stationary personnel, particularly nursing and anesthesia staff members [20].

Radiation Shielding Placed on Patients

Shields or drapes placed directly on the patient can further decrease scatter. One such shield is a small bismuth-based disposable shield (Radpad, Worldwide Innovations and Technologies). When placed between the patient and the operator and outside of the primary beam, this shield can reduce operator doses by 44% [21, 22]. Proper positioning is key, because placement of this or any high-attenuation object in the path of the primary beam can markedly increase radiation to the patient through automatic exposure control.

Lead-based surgical drapes are lightweight disposable cloths with a 0.1-mm lead equivalency that can be placed over the patient's body instead of standard surgical drapes. The lightweight drapes decrease scattered radiation to one-ninth to one-fifth of the original value. However, because they fall within the x-ray FOV, these drapes increase the overall patient entrance exposure rate 30–40% owing to compensating radiation beam adjustments made by the automatic exposure control [23].

Personal Radiation Protection Garments

Leaded aprons and thyroid shields—Fluoroscopy operators and staff need radiation protection garments that fit comfortably and provide adequate protection. Selecting from the wide variety of styles, sizes, and materials depends on radiation protection efficacy, fit, comfort, weight, durability, and ease of maintenance (Fig. 3). Styles with front closures where the fabric overlaps provide double-barrier thickness for frontal exposures of the chest, abdomen, and pelvis (Figs. 3A and 3B). Added protection of these radiosensitive areas may be desirable for operators of reproductive age. Styles that also cover the back may be heavier but offer protection for operators who expect to turn away from the patient during fluoroscopy (Figs. 3A–3D). There has been limited research regarding the efficacy of different designs of protective devices. In one study [24], the investigators evaluated four different styles of lead garments, but the results were confounded by unequal exposures. Thyroid shields typically wrap around the neck, but styles vary. Data comparing them are limited, but a thyroid collar that maximizes surface area covered may afford the most protection [24].

Wearing ill-fitting protective garments can result in insufficient protection and discomfort. Leaded aprons that are too large can allow scatter to the breast area through large armholes. They may also inflict ergonomic strain due to excess weight. Overly small garments may not cover the body sufficiently, leaving areas exposed [15].

Ergonomic issues of radiation protection garments—Despite the benefits of radiation protection garments, their weight and fit can cause musculoskeletal pain and injury, especially to the spine [25]. In a 2004 survey of the Society for Cardiac Angiography and Interventions [26], nearly 50% of respondents reported spinal problems, nearly twice the proportion reported by U.S. adults in general (27.4%) [27]. Back pain resulted in missed work for 33% of respondents, and 25% reported problems with other joints (e.g., hips, knees, ankles). Almost one-half of radiation garment wearers find the garments uncomfortable [28]. Wraparound garments are heavier but, because the weight is distributed evenly, they may offer less axial strain than garments that only shield the front. Because these issues can discourage the proper use of protective devices, appropriately fitting leaded aprons and lighter alternatives can support adherence to personal radiation protection practices.

Non–lead-based aprons and thyroid shields—Manufacturers have addressed the ergonomic issues by incorporating lead alternatives to make lighter protective aprons. Lead composite shielding materials (combined with cadmium, tin, iodine, barium, antimony, or tungsten) may decrease garment weight compared with the use of lead alone but have mixed attenuation efficiencies [29, 30] (Fig. 4A). Lead-free fabrics are made with metal powders (e.g., bismuth oxide [Bi_2O_3], gadolinium oxide [Gd_2O_3], and barium sulfate [BaSO]) with lower-energy k-edge absorption than lead, but they have mixed results [31–33] (Fig. 4B). One example is a BaSO-Bi_2O_3 composite (XPF, BLOXR Solutions). Some studies show that these lead-free or mixed lead aprons have attenuation properties equal or superior to those of classic lead aprons at selected energies across the 0- to 130-keV spectrum [33]. Another study of a lead-free apron with claimed 0.5-mm lead equivalence showed inferior attenuation efficiency compared with that afforded by a lead apron (73% higher transmission at 70 kVp and 31% higher at 100 kVp), though the lead-free apron weighed nearly one-third less [29]. In addition, the penetration through one lead-free garment at 60 kVp was 478% higher than the penetration through the equivalent lead garment [34].

Advertised attenuation efficiencies may not apply to real-world exposures, to the lower energies of scattered photons. Current standards require only attenuation efficiency measurements at a single beam energy, which does not necessarily equate to similar efficiencies at other clinically relevant broad-spectrum energies. A more applicable evaluation would be to study the attenuation efficiency of garments exposed to an energy spectrum of clinically relevant scattered x-ray beams.

Thyroid collars made with the BaSO-Bi_2O_3 composite are lightweight alternatives to the standard lead thyroid shields. The BaSO-Bi_2O_3 collars weigh 27% less than standard leaded collars and have been rated as comfortable to wear [35]. In one study [35], measured radiation attenuation provided by BaSO-Bi_2O_3 thyroid collars was comparable to that of standard lead thyroid collars (79.7% vs 71.9%). In another study [36] results with the BaSO-Bi_2O_3 collar were superior to those with lead (90.7% dose reduction with the composite collar vs 72.4% with the lead collar). Further studies are needed to compare the efficiency of different thyroid collars in attenuating scatter radiation.

Ceiling-suspended personal protective garments—To help operators avoid musculoskeletal strain, a manufacturer developed a ceiling-suspended personal protection apron (Zero Gravity, CFI Medical Solutions) (Fig. 5). This ceiling-suspended apron offers less ergonomic load to the operator without compromising radiation protection. It has been found to provide radiation protection superior to that of a standard lead apron alone or used with a standard ceiling-mounted shield [37, 38]. Survey respondents reported less back pain, more comfort, and no substantial impediment to procedure performance. Procedure time did not change with the use of ceiling-suspended aprons. The survey did not address the respondents' perceived complexity of procedures or whether operator dexterity was affected.

Radiation protection for the head and hands—Surgical caps containing the BaSO-Bi_2O_3 composite [35] are designed to protect the cranium. The measured radiation attenuation of these caps was 85.4%, and comfort was rated as high [35]. There may be added benefit to the eyes by reducing scatter from the operator's own head, because approximately 21% of the dose to the operator's eyes comes from skull-associated scatter [39]. To our knowledge, however, there are no data showing how much scatter radiation to the head actually reaches the brain. Whether use of surgical caps results in a statistically significant change in dose to the brain remains to be determined.

Radiation protection of the hands is a controversial topic [40]. The hands are closest to the patient (the source of scattered radiation) and possibly to the primary beam, so there is potential for higher exposures. Some operators consider it rarely necessary to expose the hands to the primary beam. Placing hands in the beam triggers the automatic exposure control to increase dose and scatter, especially if the hands are covered with attenuating protective material. Hand radiation shielding products may also give a false sense of security, making operators less cautious about placing their hands in the FOV [41]. Using collimation, oblique views, and intermittent fluoroscopy to avoid placement of the hands in the beam will result in dose saving to the patient and operator. As such, consistent observation of these practices should obviate additional hand protection products [40].

Nevertheless, a variety of hand-protective products are available. Attenuating gloves, the earliest radiation protection product for the hands, offer no net benefit over standard surgical gloves because the potential radiation protection obtained from the attenuating gloves is offset by the increased scattered radiation [41]. A newer radiation protection cream containing Bi_2O_3 may provide levels of radiation attenuation similar those of Bi_2O_3-loaded surgical gloves, but the data are weak, and the same issues apply as to lead gloves [33, 42]. The cream also carries a U.S. Food and Drug Administration black box warning advising caution with use in the primary x-ray field. It also warns of possible lack of effectiveness for the operator and of infection risk to the patient in the case of glove failure.

Eye protection—Radiation-induced cataracts are an avoidable occupational hazard among interventionalists. Operators can minimize radiation dose to the lens through careful attention to imaging-chain geometry, beam projection, position and head orientation of the operator, and use of shielding devices. The quality of the beam has little effect on dose to the lens [19]. The correct use of ceiling-suspended shields can reduce lens dose as much as 90–98% [13, 43–47].

Lead glasses can offer considerable lens protection, depending on style and fit (Fig. 6). Nevertheless, fluoroscopy operators wear lead glasses inconsistently, the reported adherence varying widely from 16% to 83% [43, 48–51]. Furthermore, not all lead glasses offer equal protection. When the operator and glasses directly face the x-ray source of scattered radiation (the patient), dose reduction to the right and left eyes is similar across various types of lead glasses with similar attenuation equivalents [19]. Lead glasses with lead equivalences of 0.35 and 0.5 mm and greater afforded similar levels of protection [19, 44]. However, lower lead equivalences do not ensure equivalent protection. Sturchio and colleagues [52] compared the lens dose associated with the use of lightweight glasses (0.07-mm lead equivalence) versus two models with 0.75-mm lead equivalence (sports wrap and classic glasses). Compared with the other models, the lightweight glasses transmitted more than three times the radiation to the lens when the source was in front of the operator.

Fluoroscopy operators often face the monitor with the scatter source (patient) to their side. In this configuration, as much as 80% of the exposure comes from photons traveling from below the glasses rather than toward them [19]. Each eye is exposed to different amounts of radiation, and lead glasses offer each eye different levels of protection. Studies have compared various eyewear styles, including wraparound, rectangular with a side shield, sports wrap, and newer lightweight models [19, 52]. Larger lenses conferred no additional dose reduction, even with variation in operator head positions but larger side panels offered more protection from scatter from the side [19, 52]. All eyewear styles were less effective as exposure changed from front to side. The sports wrap model had the lowest-profile side panel and offered the least side protection [19, 52]. Wraparound glasses were nearly twice as effective as rectangular glasses in reducing lateral dose to the eye closest to the source (87% reduction vs 44%) but were two-thirds as effective in reducing dose to the other eye (24% reduction vs 36%) [19]. The newer lightweight models offer equal protection with lateral and frontal exposure due to the wide area of the frame but afford inferior overall protection compared with the classic models [52].

Properly fitted lead glasses must be worn close to the eyes to offer the best radiation protection [19, 45, 52, 53]. Both wraparound and rectangular eyewear styles have been associated with marked loss of radiation protection with even 5-mm increases in the air gap between the lens and the glasses. Nearly all radiation protection is lost with a gap of 1.5 cm. If the eyewear is tilted just 10° (Fig. 6F), the air gap decreases, which can result in dose reductions of 50% [19]. However, it may not be possible to tilt prescription glasses without negatively affecting operator vision.

For a given procedure type and imaging-chain geometry, operators should position monitors and themselves to optimize eye protection [47]. The operator should wear well-fitting lead glasses with lateral coverage and stand as far from the x-ray source as is practical.

Quality Control

Although a thorough discussion of the quality control of protective devices is outside the scope of this article, interventionalists should be aware of these practices. Qualified personnel under the direction of a medical physicist perform acceptance tests on all imaging systems and personal protective devices. The acceptance tests include image quality, radiation output, automatic exposure control operation, and visual inspection of personal protective devices for physical imperfections. Radiographic, not fluoroscopic, imaging of the aprons should be performed if a device is suspected of having defects. After these initial acceptance tests, medical physicists supervise the annual performance of routine quality control tests of the devices. In addition to performing standardized quality control, we encourage operators to visually examine their aprons frequently if not daily for physical defects and imperfections. If a defect is detected, operators may themselves perform or request a radiographic examination of the apron by the appropriate staff [29].

Good Radiation Safety Practices

In 2010, the Society of Interventional Radiology and the Cardiovascular and Interventional Radiological Society of Europe released a joint statement recommending practices for reducing occupational dose [54]. We summarize and elaborate on these recommendations, focusing on exposure reduction to the operator and ancillary staff.

Wear Dosimeters Consistently and Properly

A dosimeter should be worn on the outside of the personal protective equipment at the level of the shoulders to approximate lens and thyroid exposure. A double badge system, with one dosimeter outside and one inside the apron, is preferred for estimating eye and body dose but may not be appropriate for routine use. It may have a purpose if the operator is pregnant [55, 56].

Wear Effective Personal Protection Equipment

Personnel should always wear properly fitting protective garments, report suspected defects immediately, and submit defective equipment for further evaluation.

Seek Out Appropriate Initial and Ongoing Device-Specific Fluoroscopy Training

Operators should review the essential dose reduction components of each fluoroscopy system used.

Plan Before Beginning Procedures

Operators must understand the risk-to-benefit ratio of each fluoroscopic procedure and consider alternatives or ways to reduce dose. They should carefully review anatomic and pathologic findings from previous examinations to avoid unnecessary steps and reduce procedure time and radiation exposure and identify in advance views most useful for the area of interest.

Anticipate Procedures Likely to Incur Higher Radiation Doses

Complicated procedures (e.g., transhepatic portosystemic shunt placement [51]) can take longer and incur higher doses to the patient and operator. The operator should consider varying the skin entrance port but avoid large oblique angles and overlapping fields. Obese or thick patients are likely to incur higher doses. When the patient's anteroposterior thickness increases from 16 to 28 cm, the patient dose may increase by a factor of 6 and operator dose by a factor of 4 [57].

Habitually Prepare and Use All Available Protective Shielding

Mobile shields should be prepared and arranged at the beginning of every procedure in anticipation of the distribution of scatter radiation. Passive shields should be used over and under the table. Personnel should be empowered to point out vulnerabilities and request additional shielding.

Optimize System Imaging Geometry

The inverse square principle should be observed: exposure is inversely proportional to the square of the distance from the source. The patient should be placed as far away from the source and as close to the imaging detector as practical. When possible, the operator should stand farther away from the source and the patient. Vascular access choice should be considered wisely: a study comparing radial versus femoral arterial access [58] showed that radial access was associated with 100% increases in operator radiation exposure during diagnostic coronary catheterization procedures and 50% increases during coronary interventions.

Patients are thicker in the lateral and oblique projections, so patient and operator doses can be higher as well, especially when the C-arm brings the source closer to the operator. Biplanar fluoroscopy and fluorography and the left anterior oblique view, for which the operator is on the patient's right [59], are associated with higher doses. Undertable x-ray tube systems should be used whenever possible.

Use Fluoroscopy Sparingly

Fluoroscopy should be used sparingly, and ultrasound should be used whenever appropriate. Low-dose fluoroscopic modes should be the default. The high-dose fluoroscopic mode can exceed 10 mSv/h to the operator. Changing from low-dose fluoroscopic mode to high or cine mode can increase staff dose by factors of 2.6 and 8.2 [57]. Use of fluorography, such as spot images, digital subtraction angiography, and cine imaging, should be minimized. Cine acquisition mode can exceed 50 mSv/h [57]. The lowest appropriate pulse and frame rates should be used. The default fluoroscopic frame rate should be decreased to 2–7.5 frames per second to reduce dose while maintaining adequate diagnostic quality [60]. Intermittent fluoroscopy should be used. Rather than using live fluoroscopy or a spot image, the operator should examine the last-image-hold image or saved fluoroscopic loop. Breath-holds and appropriate medications (e.g., sedation or glucagon) should be used to reduce motion artifact from the patient or bowel and decrease the need for high frame rates and repeat imaging.

Eliminate Unnecessary Radiation Exposure

Collimation reduces the dose to the patient and operator and improves image contrast. The staff should exit the room or increase their distance from the patient during digital subtraction angiography and cone-beam CT. A power injector should be prepared and used whenever possible. The operator should understand the role that automatic exposure control plays in determining image quality and dose. All unnecessary objects should be removed from the path of the primary beam, including contrast syringes, clamps, and shields. Operators should avoid exposing their hands to the radiation field.

Use Magnification Judiciously

Both geometric and electronic magnification result in increased patient dose, so magnification should be used only when it will improve efficiency. Solid-state detectors may allow electronic magnification with less dose increase than with image intensifiers [61].

Use All Available Dose Reduction Techniques

Image postprocessing techniques should be used for noise reduction and contrast enhancement. Antiscatter grids should be removed for imaging of extremities.

Promote Radiation Protection Awareness

Regular radiation safety refresher courses appropriate to each staff should be conducted. All patient dose metrics should be recorded, and staff doses should be regularly reviewed.

Conclusions

Sound radiation safety practices that maximize both protection and comfort can help fluoroscopy operators and staff enjoy long, productive careers helping patients. Striking this balance between safety and comfort is critical. Historically, interventional radiologists in private practice spent approximately 30–50% of their careers performing procedures, not all of which required fluoroscopy [62]. As interventional radiology transitions toward being an independent specialty [63, 64], we can expect to see more interventional radiologists spending a large proportion of their time using fluoroscopy [65, 66]. In parallel, other specialists are performing more fluoroscopically guided procedures [3, 8–10], often without the benefit of the in-depth radiation safety training common to radiologists.

By understanding the essentials of radiation physics, radiation protection, and the unique features of each imaging system, fluoroscopy operators and staff can capitalize on opportunities for efficiency and radiation protection while minimizing ergonomic strain. Interventional radiologists can embrace this opportunity to champion robust radiation safety practices and educate trainees, staff, and colleagues across specialties. As such, interventional radiologists can establish themselves as experts and leaders, underscoring their value to colleagues and the hospital administration.

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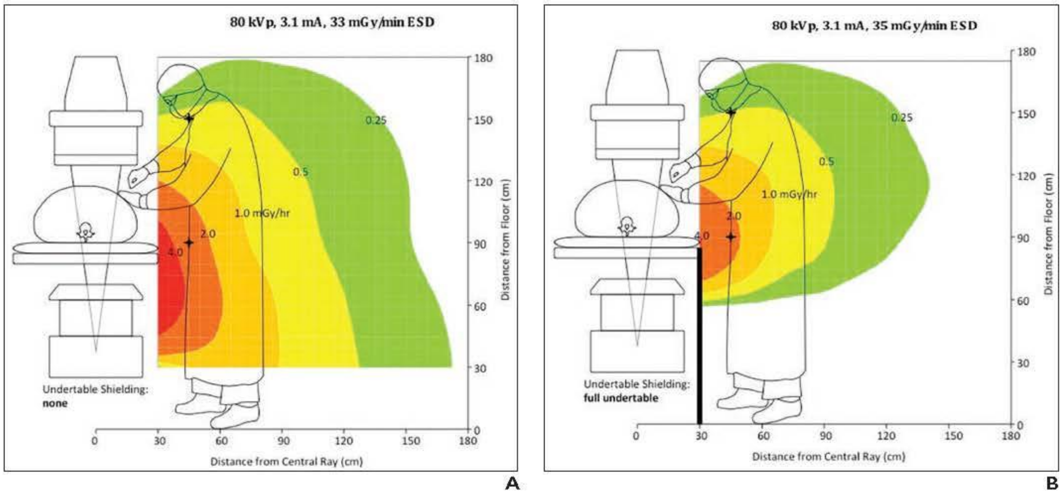

Fig. 1—Scatter radiation distribution as function of distance with undertable x-ray tube system. ESD = entrance skin dose rate.
A and **B**, Schematics and graphs show results without (**A**) and with (**B**) table skirt. (Reproduced with permission from [16])

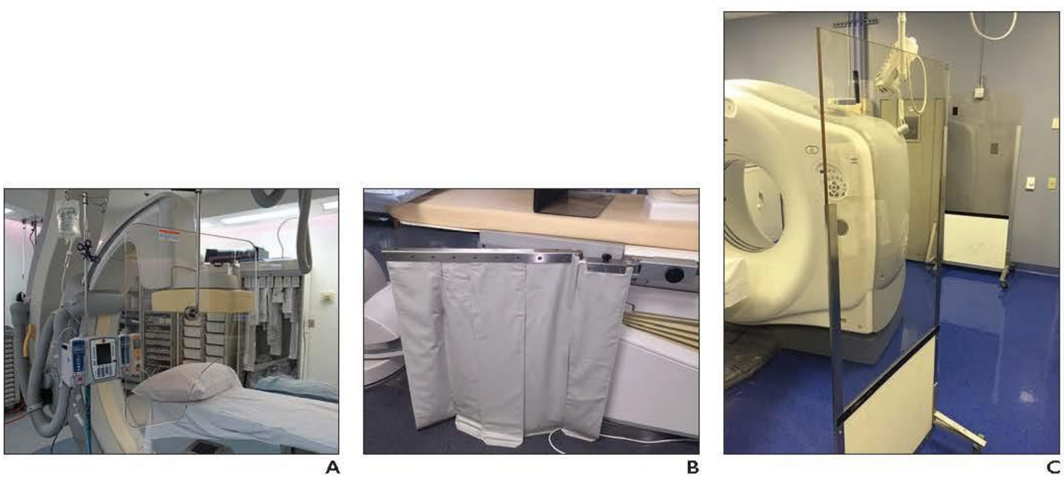

Fig. 2—Radiation protective devices.
A, Photograph shows ceiling-suspended shield.
B, Photograph shows table skirt.
C, Photograph shows mobile shield on wheels.

Fig. 3—Common styles of lead personal protective aprons.
A and **B**, Photographs show front (**A**) and back (**B**) of two-piece apron with wraparound skirt and front entry vest. Garment also has left arm shield.
C and **D**, Photographs show rear-entry single piece apron with full front (**C**) and back (**D**) coverage.
E and **F**, Photographs show front (**E**) and back (**F**) views of rear-entry single-piece apron with open back.
G and **H**, Photographs show whole-body (**G**) and close-up (**H**) views of poorly fitting oversized apron resulting in exposure through left arm hole.

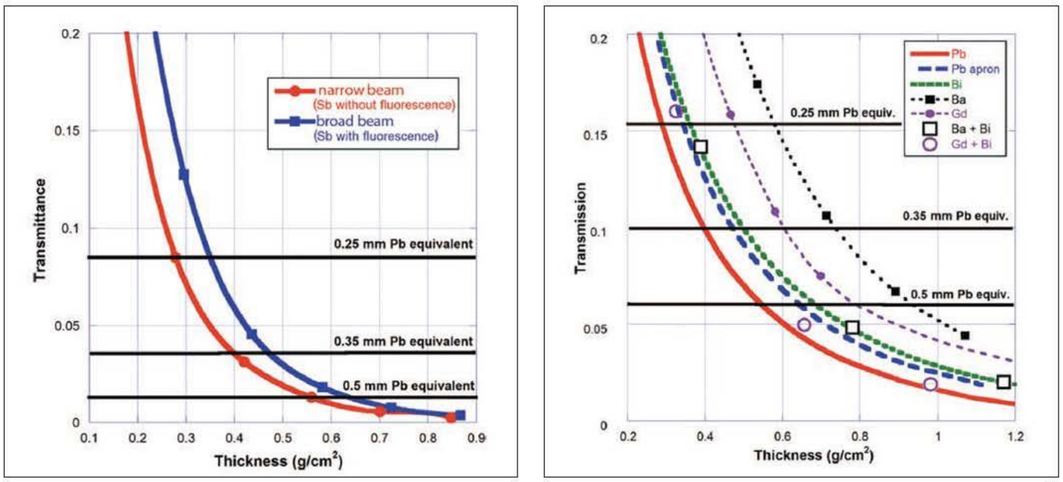

Fig. 4—Relation between shield thickness and radiation transmittance. (Reproduced with permission from [33])
A, Graph shows transmittance versus thickness measurements of several experimental materials and bilayers irradiated in broad beam geometry with 100-kV American Society for Testing and Materials (ASTM) x-ray quality.
B, Graph shows transmittance versus thickness measurements for commercial antimony-loaded radiation attenuating material irradiated with 70-kVp ASTM x-ray quality and measured in narrow beam (without fluorescence) and broad beam (with fluorescence) geometries.

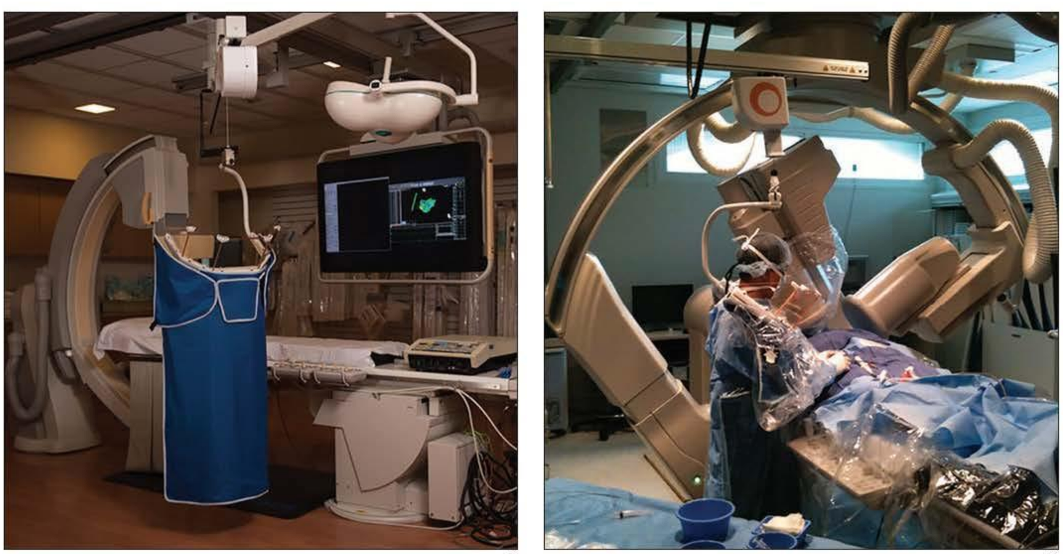

Fig. 5—Ceiling-suspended radiation protection designed to minimize both radiation exposure and body strain. (Courtesy of CFI Medical Zero Gravity)
A, Photograph shows components of system.
B, Photograph shows system in use.

Fig. 6—Lead eyewear.
A and **B**, Photographs show frontal (**A**) and lateral (**B**) views of side shield style.
C and **D**, Photographs show frontal (**C**) and lateral (**D**) views of sports wrap style.
E and **F**, Photographs show fit of eyewear in neutral position (**E**) and with slight inferior tilt (**F**) of eyewear along zygoma, which decreases scatter radiation incident on lens.

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