Radiation Safety Culture: The Way Forward in Practicing Interventional Radiology

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Abstract

Radiation dose from catheter-based interventional procedures performed in catheterization laboratories are of concern as an increase of radiation dose beyond threshold limits will be detrimental to the patient. It is important that radiation personnel understand the biological effects of radiation since patient and staff exposure may be significantly high when not adhered to radiation safety standards. Use of protective accessories, such as lead aprons and goggles, has been practiced worldwide for individual protection. Dose audit during interventional procedures is important for the benefit of the patient. Several factors including angiographic equipment, preset protocols, and tube angulations that influence radiation dose to patient and operators and hence modification on radiation safety work practices in the catheterization lab is warranted. Implementing periodic radiation safety training for occupational workers would be beneficial to practice a radiation safety culture.

Keywords

- radiation protection
- dose reduction strategies
- catheterization laboratory

Introduction

Catheter-based interventions involving fluoroscopic imaging are increasing in both radiology and cardiology as the benefits of this procedure outweigh invasive surgical interventions in most cases.

Dedicated angiography machines with high-frequency generators have the ability to impart a large amount of radiation dose to the patients with the probability of inducing deterministic and stochastic effects. Deterministic radiation-induced skin injuries range from transient erythema at low doses to dermal necrosis or chronic ulceration at very high doses.[1–4] The manifestation of radiation injury to the skin is not immediate, but usually appears days to weeks after irradiation.[5] The American College of Radiology (ACR) has set a trigger level of 3 Gy, which requires clinical follow-up for skin effects arising from complex radiologic interventions.[6] Understanding the radiation doses from interventional procedures helps in the estimation of cancer risk from a population using biologic effects of ionizing radiation (BEIR) VII risk models.[7]

Apart from patient doses, there is an increasing concern on radiation doses received by the staff involved in radiological interventions. An increase in patient dose significantly increases radiation exposure to the operators working in close proximity to the patients. Interventionalists are exposed to an average effective dose of 4 mSv about a factor of 6 higher than the doses for other medical doctor specialists, nurses, and other workers in health care.[8] The National Academy of Sciences committee on BEIR VII-phase 2 had evoked the need for occupational radiation exposures to study the effects of long-term exposures to low levels of radiations.[7] Recent studies have focused on eye lens doses. Vano et al reports that posterior subcapsular lens changes were found to be characteristic of ionizing radiation affecting 50% of the interventionalist and 41% of nurses and technicians compared with less than 10% controls.[9] Investigating the occupational doses in 25 diagnostic and therapeutic interventional radiology and cardiology procedures concluded that the interventionists and nurses received an average dose of 64 and 4 µSv, respectively, to the lens of the eye.[10] It was also found that the annual eye dose was 8.2 mSv for the interventional cardiologist and 0.5 mSv for the interventional radiologist.[11] In a retrospective study, including 129 interventional cardiologists and electrophysiologists who worked for an average of 22 years, an estimated cumulative dose to the lens ranged from 25 to 1600 mSv.[12] This illustrates that caution is warranted among occupational

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workers especially in catheterization laboratory for effective use of shields and practicing basic elements of radiation protection. This article intends to throw light into various aspects of radiation safety necessary to initiate a radiation safety culture. Hence, information on angiographic equipment, performing radiation dose audit, performing image quality analysis, dose reduction strategies, monitoring personnel dose, measuring scatter, and measuring dose to the operator are discussed in this article.

Angiographic Equipment

Interventional procedures are performed in dedicated catheterization laboratories either equipped with image intensifier (II) or flat panel detector systems (FPD). The II-based systems have been used for fluoroscopy for more than two decades while the FPD systems, on the other hand, emerged in the 1990s initially for two-dimensional (2D) projection X-ray image, and subsequently for a "real-time" fluoroscopy sequence.[13] Interventional angiography suites equipped with II or FPD have the potential to impart high radiation doses to patients if optimization strategies are not well implemented.

Many centers globally have been moving from II to FPD systems due to the varied options available, though II has been still widely used in operation theaters and angiographic suites. The transition from II to FPD system for a catheterization laboratory would require adequate justification in terms of radiation dose, image quality, maintenance, and investment. Adhering to the same optimization strategies in both II and FPD systems, radiation doses were similar; however, advantages of FPD in terms of good image uniformity, improved patient imaging accessibility due to a smaller size, the absence of geometric distortion/veiling glare or vignetting makes FPD superior to the II systems.[13] Selection of 0.4 mm Cu filtration with low-dose settings during fluoroscopy is suggestive for observing reduced radiation doses in novel FPD with real-time noise reduction algorithm.[14] Dekker et al, reported that the new generation FPDs incorporated with good image processing and noise reduction techniques results in reducing patient doses by 43% without compromising image quality and staff doses by 50% during electrophysiological interventions.[15] It is suggestive to follow stringent dose reduction strategies right from the period of initial installation when there is a transition from II to FPD systems. The patient dose and image quality in any newer modality needs to be permanently monitored, and transition from II to FPD requires careful attention.[16]

Performing Radiation Dose Audit

Radiation dose imparted to patients is measured using dose area product (DAP) meter fitted to the collimator assembly of the X-ray tube. The DAP meter is constructed using transparent plastic, and it is therefore completely unobstructive to the examination. The DAP is the most reliable measurement technique for dynamic examinations such as fluoroscopy in which the projection technique and the technique parameters are continually varying.[17–19] DAP (unit: Gycm^2) helps in the estimation of radiation doses from complex interventional examinations and provides a useful indication of overall patient dose rather than measurement of surface dose.[20,21] DAP is particularly useful for assessing and comparing radiation doses from complex interventions and in establishing diagnostic reference levels (DRLs) which serve as a reference for practicing interventionalists.

In addition to DAP, cumulative air kerma (CK) or entrance surface air kerma is incorporated in modern angiographic machines for assessment of skin dose to the patient undergoing complex interventional procedures. CK is calibrated in free air with an interventional reference point (IRP) at a location representing the patient's skin. The IRP is located 15 cm from the isocenter toward the focus of the X-ray tube for isocentric angiography machines. However, one must consider the effects of backscatter factor, table couch attenuation, and tissue absorption coefficient (f factor) for the obtained CK readings while converting to patient dose.[22] Knowledge on DAP values is also useful to compute organ doses and hence estimate the stochastic risks using Monte Carlo simulation. Previously appropriate conversion factors for various tube potential and filtration was used to convert DAP to an effective dose.[23] Currently, these calculations are performed using commercially available software such as PCXMC Monte Carlo simulation by qualified medical physicists.

►**Table 1** shows the reported DAP and effective dose values for common diagnostic and therapeutic interventional procedures in comparison to chest radiographs.[24] As part of dose audits over the past decade, local, and regional DRLs were set up for radiological investigations in our tertiary referral center. ►**Table 2** shows radiation dose audit of interventional procedures from our center in comparison with DRL values reported by Hart et al.[17,18,25–34] The values reported from our study are well within the reported DRLs, ensuring periodic dose monitoring and modification of work practices. Interventional procedures involve extensive use of tube angulations such left anterior oblique (LAO), right anterior oblique combined with cranial and caudal angles (CAU). It is reported that coronary angiography (CAG) procedures involving oblique projections coupled with shallow or steep cranial or caudal angulation would help in visualizing cardiac vessels distinctly without any overlap, thus providing sufficient reference image for intervening the lesions.[35–37] At such instances, the source to imaging detector increases imparting higher radiation doses to patients. For CAG procedures which adopt standard angiographic tube angulations, the contribution of radiation doses to the overall DAP from LAO 45 degrees to CAU 35 degrees and posterioanterior (PA) to CAU 40 degrees were 16 and 11%, respectively, due to high tube potential of 120 kV and tube current of 21.4 mA compared with other angiographic tube angulations.[33] Hence, adequate knowledge with the use of angulations is required so as to avoid deterministic risks.

Table 1 DAP and effective dose from interventional diagnostic and therapeutic procedures[22]

Procedures	Mean DAP ($Gycm^2$)	Mean effective dose (mSv)	Equivalent number of PA chest radiograph (each 0.02 mSv)
Micturating cystourethrogram	6.4	1.2	60
Hysterosalpingogram	4	1.2	60
Barium swallow		1.5	75
Fistulogram	6.4	1.7	85
Myelography	12.3	2.46	123
Barium meal		2.6	130
Sinography	16	4.2	210
Barium enema		7.2	360
Lower extremity	14	3.5	175
Coronary angiography	26	3.1	155
Cerebral angiography	85.7	3	150
Thoracic aortography	34.5	4.1	205
Pulmonary angiography		5	250
Peripheral arteriography	27.2	7.1	355
Abdominal aortography		12	600
Renal angiography	86	13.7	685
Upper extremity arteriography	18	0.9	45
Nephrostomy	13	3.4	170
Pacemaker implant	17	4	200
Thrombolysis	13.5	3.5	175
Lower extremity arteriography	18	4.5	225
Vascular stenting	40	10.4	520
Renal angiography	81	11.7	585
Insertion of caval filters	48	12.5	625
Percutaneous transluminal coronary angioplasty, stent placement	58	15.1	755
Radiofrequency ablation		17.3	865
Mitral valvuloplasty	162	29.3	1,465
Cerebral embolization	202	5.7	285
TIPS	206	53.6	2,680

Abbreviations: DAP, dose area product; DRL, diagnostic reference level; TIPS, transjugular intrahepatic portal systemic shunt.

Performing Image Quality Analysis

Image quality plays a vital role in conveying diagnostic information to the radiologist. It is assessed critically while optimizing patient dose for various radiological examinations. Image quality is analyzed and quantified using three distinct terms, namely, contrast resolution, spatial resolution, and mottle (noise). Spatial resolution is the ability to produce an accurate and clear image (ability to image objects that have high subject contrast, such as bone–soft tissue interface, a calcified lung nodule). The spatial resolution of the image can be obtained for various field sizes using a fluoroscopy resolution test tool. The number of lines per mm can be measured for different field of views (FOV) and for different dose rates. Contrast is the difference in the image gray scale between closely adjacent regions on the image. Contrast resolution is the ability to distinguish one soft tissue from another without regard to size or shape. Contrast detail measurements are a reasonably quick, repeatable, and widely used method for assessing the image quality. Clinical images can be assessed subjectively and objectively. For subjective assessment, clinical images acquired using different dose rates can be elicited from the workstation. The images are blinded and assessed by interventionalists on the five-point Likert scale. The results can be verified by measuring the signal to noise ratio (SNR) and contrast to noise ratio (CNR) using Image J software (National Institute of Health, Bethesda, Maryland, United States). A region of interest (ROI)

Table 2 Radiation dose audit of interventional procedures reported from our center in comparison with DRLs

Procedure	*N*	Mean FT (min)	Mean DAP (Gycm^2)	DRL DAP (Gycm^2)
Micturating cystourethrogram[24]	73	2.7 (1.1–6.5)	3.76 ± 0.26 (0.43–9.26)	12[23]
Hysterosalpingogram[25]	8	0.69 (0.27–2.03)	1.18	2.9[23]
Barium swallow[26]	32	2.5 (1.08–7.11)	2.36	9[23]
Barium meal[26]	31	5.65 (3–10.2)	4.26	14[23]
Barium enema[26]	17	6.34 (3.32–7.59)	11.21	40[23]
Cerebral angiography[27]	40	7.93 (0.8–30.8)	127.5	180[31]
Cerebral embolization[28]	32	36.61 (11.14–70.28)	234.35	487[31]
Hepatic embolization[29]	9	14.91 (3.06–26.63)	161.97 ± 45.98 (18.79–395.33)	160[32]
Renal embolization[29]	17	19.76 (6.57–40.68)	138.61 ± 16.68 (60.84–299.75)	160[32]
Splenic artery embolization[29]	7	20.56 (12.8–29.4)	162.17 ± 45.6 (62.47–394.25)	160[32]
TACE[29]	9	21.33 (6.75–30.95)	141.6 ± 24.97 (43.64–292.16)	160[32]
TIPS[30]	19	19.2 (4–32.1)	63.86 (2.12–117.07)	–
Percutaneous transluminal coronary angioplasty single stent[16]	18	14.57 (5–29.9)	48.67 ± 24.95 (21.3–98.1)	50[23]
Coronary angiography[31]	140	3.24 (0.5–10.51)	13.99 (4.02–37.6)	29[23]

Abbreviations: DAP, dose area product; DRL, diagnostic reference level; FT, fluoroscopic time; TACE, transarterial chemo embolisation; TIPS, transjugular intrahepatic portal systemic shunt.
Note: The DRLs are reported from various literatures.

is placed in the organ of interest to measure the average pixel intensities and compared with background noise. The greater the SNR, the better the image resolution. The SNR and CNR are calculated using the formula[38]:

$$\mathrm{SNR} = \qquad\qquad \mathrm{CNR} =$$

- ΔI: Change in intensity caused by lesion
- I_b: Average background intensity
- σ_I: Standard deviation of background intensity due to noise

A study on optimization of dose protocols was performed in interventional cardiology for coronary angiography procedures. An ROI was placed in the heart which was the desired area of interest for examination. The SNR and CNR were calculated using the formula. The SNR for low and medium dose rate fluoroscopy images were 4.09 and 5.65, respectively, and CNR for low and medium dose rate fluoroscopy images were 0.1 and 0.13, which did not vary significantly. Hence, it was found ideal to adopt low-dose protocol for fluoroscopy which reduced the overall radiation dose by 14% maintain acceptable image quality of diagnostic accuracy (►**Fig. 1**).[33]

Dose Reduction Strategies

The catheterization laboratory should consider the risk/benefits of the examinations and adopt certain dose-reduction strategies suggested as follows[39]:

1. Position patients properly. Anatomical regions other than the ROI should be kept away from the field as much as possible (e.g., the arms of the patient may be kept under the head).
2. Remove antiscatter grid for pediatric and thin patients. Keep the image receptor close to the patient.
3. Selection of 0.4 mm Cu filtration with low-dose settings during fluoroscopy.

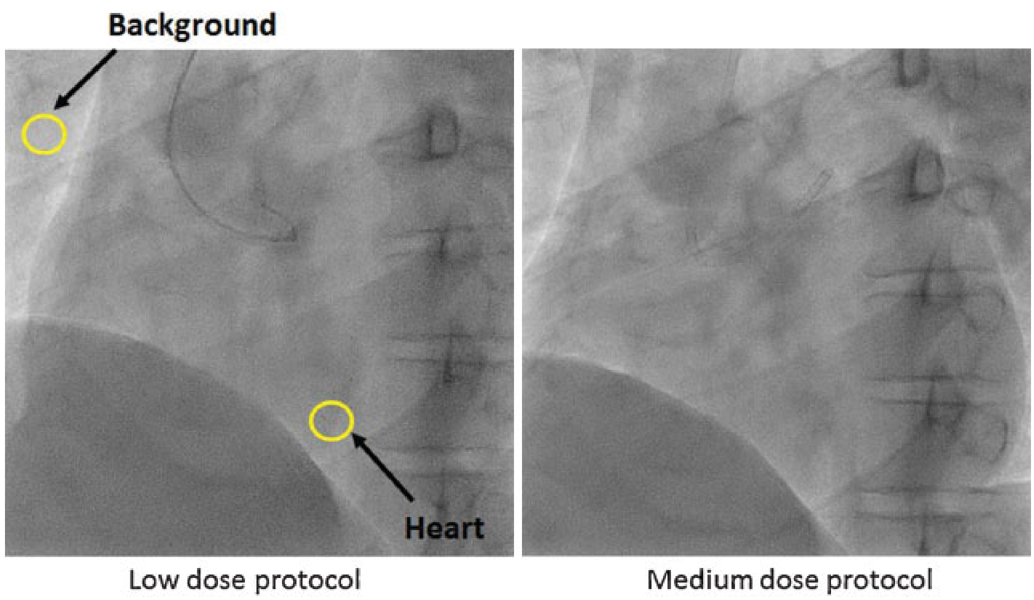

Fig. 1 (**a**) Fluoroscopic image acquired using low dose protocol. ROI placed in heart and background to measure the pixel intensities and noise. (b) Fluoroscopic image acquired using medium dose protocol. ROI, region of interest.

4. Cine runs, digital fluorography, high-dose–rate fluoroscopy, and high-magnification modes must be used sparingly and judiciously at all times.
5. Use last image hold (or) last image freeze technique with electronic collimation.
6. Keep the detector close to the patient.
7. Maintain adequate distance for patient's skin surface to the X-ray tube. The minimum focus to skin distance may be 30 cm.
8. Fluoroscopy should be performed intermittently and judiciously. Stay off the fluoroscopy pedal whenever possible to minimize beam on time.
9. Pulsed fluoroscopy should be preferred over continuous fluoroscopy modes for dose reduction. Use of 12.5 f/s during cine runs and increasing the frame rate to 25 f/s during postprocessing will halve the radiation doses contributed from cine runs acquired with 25 f/s. A reduction of the fluoroscopic pulse rate from 15 to 7.5 f/s with a fluoroscopic mode to low dose reduces the radiation exposure by 67%.
10. The selection of the size of FOV is crucial, since the severity of a radiation wound may depend on the size of the radiation field. Tighter collimation of the beam area is recommended for reduction of stochastic risk.
11. Use steep angulations judiciously. Constantly change tube angulations to avoid accumulation of radiation dose to specific region on the skin surface.
12. Minimize the use of lateral (LAO) projections and steep cranial angles.
13. Contrast injection using remote injectors should be synchronized with the image acquisition.
14. It is a good practice to periodically record source to image distance, DAP values, the time duration during fluoroscopy, the number of cine runs, and digital image acquisitions. This is useful to formulate local reference levels and compare it with the guidance levels.
15. With the use of digital fluoroscopy systems, it is possible to acquire (and delete) images. Hence, there may be a tendency to obtain more images than necessary leading to irradiation of the patient more than is clinically necessary; this demands adequate justification.
16. Make sure that the monitors in the catheterization laboratory are regularly calibrated. Poor monitor setup in the console as well as inside the catheterization laboratory (e.g., low illumination, contrast or spatial resolution) could lead to unnecessary repeated exposures, due to poor diagnostic information.
17. Periodic quality assurance is mandatory for all radiation-based modalities. Make sure that the equipment complies with all safety and standard parameters set by the manufacturers at the time of installation.
18. Communication between staff and operator, in high-dose cases, is essential. The staff should notify the physician operator during the procedure when CK is more than 3 Gy and then every 1 Gy after that.

Radiation Safety

Monitoring Personnel Doses

Personnel working in catheterization laboratories are exposed to scatter radiation emanating from the patient undergoing fluoroscopic examinations. Routine personnel monitoring is performed using thermoluminescent dosimeter (TLD). All personnel who are exposed to 3/10th of the annual dose limit of 20 mSv/y should be issued with a TLD badge. The TLD badge worn at the chest level indicates the whole body radiation exposure. While wearing lead aprons, TLD badge should be worn inside the apron as per the Atomic

Energy Regulatory Board (AERB) guidelines.[40] Dosimeters such as TLD and optically stimulated luminescent dosimeters are tissue equivalent and hence extensively used for monitoring personnel radiation exposure at specific exposure sites such as eyes, hands, and legs during interventional procedures. The calibrated dosimeters fixed to forehead can be used to approximate the eye doses. Real-time monitoring of personnel doses can also be performed using digital pocket dosimeters. These dosimeters can be worn by the personnel in catheterization laboratories, which indicates dose in microSievert and an alarm indicates exceed of dose limits which require modification of work practice.

Measuring Scatter Radiation

Periodic radiation survey should be performed, especially in catheterization laboratories, to check for any leakage or faulty equipment leading to higher exposures and measure the scatter radiation behind various barriers. In addition, personnel dosimetry can also be performed for various imaging systems. A survey is performed by simulating clinical setup using an anthropomorphic phantom or water phantom placed under the radiation beam. The scatter radiation is measured using a survey meter placed at various locations inside and outside the catheterization laboratory. The dose rate behind barriers should not exceed 40 mR/wk as per the AERB guidelines.[41] Kuon et al performed dose mapping using anthropomorphic phantom and measured operator radiation doses for various tube angulations adopted in catheterization laboratories. A 7.6-fold increase in operator doses was observed in LAO 45 to CAU 35 degrees compared with PA to CAU 30 degrees.[42] Similarly, Vano et al performed a study on scatter radiation doses using acrylicphantoms of thickness ranging from 16 to 28 cm for different dose protocols. The scatter radiations to the eye lens of the operator from fluoroscopy were 6.0 and 34.5 µSv/min using low- and high dose, respectively. For digital subtraction angiography (DSA), typical doses to the eye lens ranged from 0.77 to 3.33 µSv per image.[43]

Radiation Safety of Operator

Occupational radiation workers should always be protected and monitored periodically. Individual TLD badges are provided to all occupational workers as per the regulatory guidelines of the AERB. The basic radiation protection strategies are governed by three radiation hazard reduction methods: time of the radiation exposure, distance between X-ray source and object and shielding. Radiation dose is directly proportional to the time of exposure; hence, the minimum examination time should be spent for fluoroscopy, cine runs, and DSA. The inverse square law states that radiation is inversely proportional to the square of the distance. Maintaining adequate distance from the source is an effective radiation protective method for operators. It also implies that an increase in distance between patient and receptor will increase in radiation exposure to the operator due to increase in scatter. During interventions, the control of both time and distance by the operator is limited; the interventionalist needs to stand close to the source, and the fluoroscopy time depends to a large extent on the complexity of the case. Thus, optimum shielding is important. Some salient points on the safety of operator are given below:

Table 3 Factors that modify scattered radiation doses at eye lens level[41]

Dose modifying factors	Factor value	
	Maximum	Mean
Increasing factors		
Angulation	6	2.0
Use of biplanar system	7	3.5
Distance to patient	4	2.0
Procedure complexity	4	2.0
Decreasing factors		
Collimation	0.25	0.5
Use of goggles (0.5 mm lead)	0.03	0.03[a]
Use of ceiling mounted barrier (1.0 mm lead)	0.015	0.03[b]

[a]With assumption that goggles are typically worn throughout the procedure.
[b]With assumption that the ceiling barrier is not always used throughout the procedure.

1. Safety accessories should be prudently used. Operators should wear lead garments/aprons (minimum 0.35–0.5 mm lead equivalence [pbeq]), thyroid collars, lead goggles, and lead-equivalent caps during interventional procedures.
2. Additional shielding such as the use of ceiling-mounted barriers and lead drapes for the legs. Lead glasses can provide dose reduction factors of 4–5; however, the dose reduction depends on the design of the glasses.[44] ►**Table 3** shows the factors reported by Vano et al that modifies scatter radiation dose to the eye lens[43].
3. Keep hands out of the primary radiation beam during the procedure. At instances during unavoidable situations use hand gloves.
4. It is mandatory for all interventionalists to use personnel monitoring device for all procedures.
5. Maintain maximum distance from patient and X-ray tube whenever possible.

Conclusion

Interventional procedures are practiced more widely. A systematic review of interventional procedures through structured audit would facilitate the development of new standards in radiation protection. Though structured radiation safety protocols are adopted, chances of recruiting higher exposure factors and radiation doses are possible if proper quality assurance is not performed to high-end modalities.

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