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Radiation Protection in Interventional Radiology

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Abstract

There has been a rapid development in the field of interventional radiology over recent years, and this has led to a rapid increase in the number of interventional radiology procedures being performed. There is, however, a growing concern regarding radiation exposure to the patients and the operators during these procedures. In this article, we review the basics of radiation exposure, radiation protection techniques, radiation protection tools available to interventional radiologists, and radiation protection during pregnancy.

Keywords
- ALARA
- interventional radiology
- radiation protection

Introduction

There has been a rapid increase in the number of interventional radiology (IR) procedures performed in the last decade. As the number and complexity of IR procedures being performed increase, this leads to increase in radiation exposure to both patients and staff. This high radiation exposure can lead to the occurrence of deterministic effects in both patients and staff, and these vary from transient erythema to skin necrosis.[1–3] Also, all irradiated patients are at risk of an increased incidence of stochastic injuries. Although IR differs from diagnostic imaging in the sense that IR procedures are usually therapeutic and, in most cases, the risk associated with radiation exposure is less than the therapeutic effect.[4] The radiation exposure to the staff and patients should be minimized by using the ALARA principles—as the radiation protection is optimized when exposure is "as low as reasonably achievable, economic, and societal factors are being taken into account.[5]"

Deterministic Effect

Deterministic health effects are those in which the severity of the effect is directly proportional to the dose of radiation above a threshold. The threshold is different for different individuals and is subject to biological variation. Examples of deterministic effects include skin injury, hair loss, and cataracts. According to the reports to U.S. Food and Drug Administration (FDA) and literature, the frequency of injury is between 1:10,000 to 1:100,000 procedures.[6]

The skin is the tissue of major concern in interventional fluoroscopy procedures as the skin is the site where the radiation enters the body; thus, it receives the highest radiation dose out of any body tissue. The Center of Disease Control and Prevention has classified the deterministic effects of single-delivery radiation dose to the skin of the neck, torso, pelvis, buttocks, and arms into five bands (A1, A2, B, C, D) based on skin dose range, national cancer institute skin reaction grade, and approximate time after the onset of effect.[7]

Stochastic Effect

It is a type of radiation effect in which the severity of the effect is independent of the total dose, but its probability increases with the dose increase. An example of this effect is radiation-induced cancer, although the probability of radiation-induced malignancy caused by an invasive procedure is

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Table 1 Guidelines for patient radiation dose reduction

Preprocedure planning	Individual training: All operators should be trained according to the institutional requirements for fluoroscopy use All staff members should receive an initial training course in patient radiation management before they start working in the IR suite with refresher training courses at least annually Equipment: Only rooms with proper radiation measuring equipment should be used for procedures that have high radiation exposure Patient consent: Radiation risks associated with IR procedures should be discussed with the patient while obtaining procedural consent when the risk radiation exposure associated with a procedure is high, and the patient is in a high-risk category Procedure planning: Evaluation of patients should be done with non-invasive cross-sectional imaging modalities that do not require ionizing radiation use whenever possible. If ionizing radiation producing modalities are used, dose reduction should be made to decrease total-patient radiation dose
Procedural planning	Procedural radiation monitoring: This should be done throughout the procedure, and the operator should be notified when the pre-defined radiation dose threshold is crossed Dose minimization techniques: Pulse fluoroscopy should be used at the lowest pulse rate, which yields adequate quality image, care should be taken to minimize fluoroscopy time and fluoroscopic images captured, and appropriate collimation should be used
Postprocedural care	Dose documentation: Radiation dose should be recorded in the medical record according to SIR guidelines.[11] Patient follow-up: If the patient receives significant radiation during the procedure, they should be followed up after the procedure

Abbreviation: IR, interventional radiology.

small compared with the natural frequency of malignancies.[8] When treating pediatric and young adult patients or performing procedures which involve substantial absorbed dose to radiosensitive organs, it is crucial to consider the effects of stochastic effect in the risk–benefit analysis.

Patient Dose

In the 1990s, the FDA reported various radiation-induced skin injuries, which promoted the development of guidelines to document radiation use.[9] In 2008, the American College of Radiology (ACR) published its recommendations on patient radiation exposure in medicine, which included diagnostic imaging procedures and interventional procedures.[10]

Management of radiation dose requires a holistic approach, which includes pre-procedure planning, intraprocedural management, postprocedural care, and periodic quality assessment. Complete guidelines are available at https://www.jvir.org/article/S1051-0443(09)00344-3/pdf; however, a summary is present in ►**Table 1**.

Measurement of Occupational Exposure

Dose limits to workers are expressed in the form of equivalent dose in an organ or tissue (HT) for exposure of part of the body, and effective dose (E) for exposure of the whole body, both of them use the SI unit sievert (Sv).

Equivalent dose is measured by multiplying the radiation weighting factor by mean absorbed dose in a tissue or organ, T, which is measured with the personal help dosimeters, and effective dose (E) is the weighted sum of all equivalent doses in all specified tissues and organs of the body.

In the United States, the estimate effective dose is calculated by combining the Hp,[10] which represents the dose equivalent in soft tissues 10 mm below the surface of the body at the location of the dosimeter, from both the body and collar dosimeters:

$$E(\text{estimate}) = 0.5\ Hw + 0.025\ HN$$

HW= Reading from dosimeter at waist or chest under the apron

HN= Reading from dosimeter at the neck outside the apron

Occupational Dosimetry in the Interventional Radiology Suite

The dosimeter has to be used by IR staff during the procedure, and the radiation dose is monitored monthly, to allow identification of practices leading to high personal dose and implementation of work habit changes.

The International Commission of Radiological Protection recommends using two dosimeters by IR staff, one under the apron and one at the collar above the lead apron.[12] In pregnant workers, the fetal dose is estimated by the use of a dosimeter placed at the mother's abdomen, under the radiation protection garments.

Dose Limits

The dose limits are maximum values of radiation exposure, which ideally should not be reached. Two types of occupational dose limits have been defined: those that establish an acceptable risk level for stochastic effects and those intended to protect specific organs or tissues.[5,13] The dose limit recommendations by U.S. National Council on Radiation Protection and Measurements are given in ►**Table 2**.

Table 2 NCRP recommended dose limits for occupational exposure (adapted from Report No. 116—Limitation of Exposure to Ionizing Radiation)

Dose quantity	Effective dose (annual)	Effective dose (cumulative)	Equivalent dose to lens of the eye	Equivalent dose to skin	Equivalent dose to extremities
NCRP maximum permissible dose	50 mSv/y	10 mSv x age (y)	150 mSv/ y	500 mSv/y	500 mSv/y

Abbreviation: NCRP, National Council on Radiation Protection and Measurements.

Evaluation of Personal Dosimetry Data

The personal dose record contains information on effective dose E, equivalent dose to the lens of the eye from the dosimeter worn at collar level or thyroid shield and equivalent dose to hand from a ring or bracelet dosimeter; these readings vary based on the number, type, and location of personal dosimeter used. These personal dose records should be reviewed by the department's radiation safety section to ensure that the dose limits are not exceeded. If the monthly exposure reaches 0.5 mSv for an effective dose, 5 mSv for the dose to the lens of the eye, or 15 mSv to the hands or extremities a radiation safety officer or a medical physicist should investigate to determine the cause of unusual dose and should make suggestions to keep the worker's dose low.

These investigations include checking the validity of the dosimeter reading and evaluating changes in the operator's work habits if there is a temporary increase. If the increase is not temporary, the working habits of the individual should be observed over a series of representative procedures. After the cause(s) of high personal dose levels are identified, then recommended changes to work practice should be implemented, which are then checked with a real-time dosimeter, which can provide immediate feedback about the radiation dose levels.

Radiation Protection

Three basic principles are at play, time, distance, and shielding are at play to achieve radiation protection. In fluoroscopy-guided interventions, the time spent checking the C-arm fluoroscopy is directly related to radiation exposure. Time exposure of the staff should be ALARA as generally less exposure time correlates to less radiation dose.[14] The fluoroscopy time is often used as an indicator of procedural dose, but the actual correlation is very poor, and therefore fluoroscopy time individually should not be used as the dose indicator.[15] Total fluoroscopy time during an IR procedure can be reduced by optimizing the number of fluoroscopic images captured, the number of x-pulses generated per image, number of runs, and their duration and frame rate.

A greater distance from the source of radiation can also reduce radiation exposure, as the amount of radiation exposure is inversely proportional to the square of the distance.[16]

Radiation Protection Tools

The primary source of radiation exposure to the operator and staff is the scatter from the patient undergoing the procedure; this can usually be reduced by controlling the patient dose. Nevertheless, to prevent complications from chronic radiation exposure, protective tools should be used to limit the occupational radiation dose to an acceptable level.

Radiation Shields

Architectural Shields

Architectural shielding primarily denotes the lead shield, which is built into the walls of IR suites. Rolling and stationary shields rest on the floor of the suite; they are constructed by using transparent-leaded plastic and are useful for providing additional shielding to both operators and staff. These shields are particularly very useful for nurses and anesthesia personnel working in the IR room.[17]

Mobile and Fixed Shielding

A variety of shields are available in a fluoroscopy suite for radiation protection. These include table skirts, ceiling-suspended shielding, and mobile shields on wheels. The shields work by decreasing the scatter radiation from the patient to the operator and the staff, which is the main mechanism of radiation exposure. Equipment-mounted shielding includes the protective drapes that are suspended from the tables and the ceilings. Protective lead curtains are detachable devices that can be placed on either side of the table where the operator is working; they help prevent the radiation exposure to lower extremities of the operator, which are otherwise not protected with the help of a lead apron.[18] In a study published by Shortt et al, the use of protective lead curtains under the table showed statistically significant dose reduction in lower extremities as compared with control (Siemens Angioskop C-Arm undercouch fluoroscopy systems [Siemens Medical Solutions, Forchheim, Germany]).[19]

Ceiling suspended shields are generally made out of transparent leaded plastic and should always be used in lengthy procedures. They are most useful when they are positioned close to the patient's skin; they work by reducing the scatter radiation to the operator. When placed at an appropriate location and angle, they can reduce the radiation exposure to the lens of the eye significantly.[20,21] The reduction in the radiation can be as much as 90 to 98% depending on the location of the X-ray source and the shield.[22]

Radiation Shielding Placed on Patients

Disposable protective drapes or shields, which can be placed directly on patients, drastically decrease the scatter radiation. RADPAD (Worldwide innovations & technologies, Inc., Kansas City, Kansas) is one such shield; it is available as a sterile surgical drape and contains bismuth and barium as radiation protection materials. It should be placed appropriately on the patient between the image intensifier and the operator to reduce scatter radiation. Proper positioning of RADPAD is critical; if it is placed in the path of the primary beam, it can increase the radiation to the patient drastically. Various types of RADPAD are available in the market based on the procedure being performed, and these include RADPAD peripheral shield with absorbent, RADPAD biopsy shield with absorbent, RADPAD Jugular Access/TIPS shield with absorbent, RADPAD biliary shield with absorbent, RADPAD fenestrated radial entry shield with absorbent, and RADPAD infant collimation shield.

In IR suites instead of standard surgical drapes, sterile lead-free disposable drapes can be used, which are made of lightweight disposable cloth with a 0.1mm lead equivalency. These drapes are simple to position and do lead to a significant reduction in radiation exposure, varying from 14% up to 94%.[23–25]

Personal Radiation Protection Garments

Leaded Aprons and Thyroid Shields

Lead aprons and thyroid shields are the principal radiation protection tool for interventional radiologists, and they should be worn at all times during the procedure. The radiation protection provided by these lead aprons is similar to a 0.25 to 1 mm thick lead. Ninety percent or more reduction of scatter radiation is observed when lead aprons with 0.5 mm thickness are used.

The selection of aprons and thyroid shields from a wide variety of styles, sizes, and materials depends on radiation protection efficacy, fit, comfort, weight, durability, and ease of maintenance. Different designs of lead aprons are available in the market. These include aprons with only front covers, aprons that wrap around the body, and two-piece garments with vest and kilt. Styles with front closures provide a double barrier of thickness to the chest, abdomen, and pelvis in the front as the fabric overlaps her;, this may be desirable to operators of reproductive age. The aprons that cover the back are heavier than others, but they protect the back when the operators turn away from the patient during fluoroscopy. Any of these designs can be used, but the apron that is selected must fit properly and give adequate coverage at the neckline and armholes.[26]

Thyroid shields are also available in various styles, but all of them wrap around the neck. They are especially recommended for personnel who receive monthly collar radiation monitor readings over 4 mSv and are below 40 years of age due to the risk of radiation-induced thyroid cancer.[27,28]

Ceiling-Suspended Personal Protective Garments

Ceiling suspected personal protection apron (Zero Gravity, CFI Medical Solutions) has been developed to reduce fatigue and prevent orthopaedic injuries in operators, which occur from wearing heavy protective apparel.[29] They utilize a suspended 1.0 mm lead body shield, which engages magnetically to a vest worn by the operator, which allows it to move in sync with the operator; also, it employs a 0.5 mm lead equivalent acrylic face shield that protects the head, eyes, and neck of the operator. These ceiling-suspended aprons provide superior operator protection as compared with conventional lead aprons with under table shield or ceiling mount shields. They have an added advantage of being more flexible, which allows clinicians freedom of movement during challenging procedures.

Eye Protection

Radiation exposure to the eye lens can lead to the formation of cataracts until recently maximum permissible dose for the lens is 150 mSv per year, but now new data has shown that the threshold might be significantly lower or even zero.[30,31] Operators can minimize radiation dose to the lens by paying attention to imaging-chain geometry, beam projection, position and head orientation of the operator, leaded eyewear, and ceiling-suspended shields. Lead glasses with different styles and fit provide different lens protection, although glasses with lead equivalences of 0.35 and 0.5 mm and higher provide similar protection.[32,33] Large-sized lens glasses (at least 27 cm^2 per glass) and those with large side panels are preferred.[34,35] There are various types of eyeglasses; these include fit-over glasses, wraparound, rectangular with a side shield, sports wrap, and newer lightweight models.

Typically, during fluoroscopy, the operator's head is placed at an angle to the scatter volume because of which the operator's eyes are exposed to radiation from the side; therefore, they should use glasses designed to block side exposure. All eyewear styles are found to be less effective as the exposure is changed from the front so side, but the sportswear model has the lowest profile side panel and therefore offers the least protection. The newer lightweight models are comfortable to wear on a regular basis as they are not heavy, they also provide equal frontal and lateral protection due to the wide area of the frame, but the overall protection is inferior to the classic models. Finally, to attain proper radiation protection, lead glasses should have a good fit.

Radiation Protection for the Head and Hands

For cranial protection disposable, lightweight, surgical caps containing two layers of barium sulfate-bismuth oxide composite can be used.[36] Hands are the closest body part of the operator to the patient and the primary beam, so they can potentially be exposed to a very high radiation dose. Most operators believe that instead of using hand radiation shielding, using collimation, oblique views, and intermittent fluoroscopy to avoid hand placement in the beam results in more radiation protection to the patient and operator.

A variety of hand protective products are still available in the market for operators to choose from. Some products that are most commonly used include attenuation gloves, and radiation protection creams containing bismuth oxide.

Quality Control

It is an essential part of radiation protection in any IR department. Qualified personnel with medical physicists help perform acceptance tests like image quality, radiation output, and visual inspection of protective devices on all image systems and personal protective devices. These quality control tests have to be performed annually under the medical physicist.

Good Radiation Safety Practices

The Society of Interventional Radiology and Cardiovascular and Interventional Radiology Society of Europe published occupational radiation protection in IR guidelines in 2010. These guidelines provide some techniques that can be implemented by all IR departments to decrease the patient dose, scatter dose, and occupational dose. Key points are mentioned below[37]:

1. Minimize fluoroscopy time
2. Minimize the number of fluoroscopic images
3. Use available patient dose reduction technologies
4. Use good image chain geometry
5. Use collimation
6. Use all available information to plan the interventional procedure
7. Position yourself in a low-scatter area
8. Use protective shielding
9. Use appropriate fluoroscopic imaging equipment
10. Obtain appropriate training
11. Wear your dosimeters and know your own dose

Radiation Protection during Pregnancy

The risk of adverse health effects to the embryo or fetus is extremely low or possibly nonexistent when the radiation exposure is lower than 100 mGy. Radiation exposure can lead to two types of adverse health effects to the conceptus—tissue reactions (i.e., deterministic effects—congenital disabilities, pregnancy loss, mental retardation, growth retardation) and stochastic effects (damage to a single cell that is enough to cause a mutation which increases the risk of cancer as the dose increases). The risk of these adverse health effects depends on the gestational age during which the exposure occurred (maximum risk during the preimplantation and organogenesis, second-trimester exposure, and the least risk in the third trimester).[38]

In the United States, the National Council on Radiation Protection and Measurements (NRCP) recommends limiting exposure to a monthly equivalent dose of 0.5 mSV once the pregnancy is identified.[39] The Nuclear Regulatory Commission has declared a regulatory limit of 5 mSV for the entire duration of pregnancy.[38] The dose of exposure to the conceptus can be approximated as one half of the personal equivalent dose at 1 cm, Hp (10), for the dosimeter placed on the waist/abdomen.[40] The employer must evaluate and ensure that the conceptus dose is kept below the recommended threshold throughout the gestation period.

For monitoring radiation exposure, the use of a single personal dosimeter worn under any protective apron at the level of the waist is recommended. An additional dosimeter can also be placed on the mother's abdomen. These readings should be monitored monthly. Any worker contemplating pregnancy can also request a waist/abdominal badge.

Workplace Injury Illness Prevention Programs are mandatory in 15 states in the United States to provide hazard awareness training to the employees upon initial hire and subsequently annually. Counseling on the potential risks of radiation exposure to pregnant workers and their partners, if possible, is an integral part of radiation protection programs.[38]

Following work modifications are recommended whenever possible:

1. Minimizing fluoroscopy time (prohibiting less-experienced workers from operating the fluoroscopy controls).
2. Substituting ultrasound for fluoroscopy guidance if it does not affect patient outcome.
3. Carefully planning the intervention may reduce unnecessary fluoroscopy.
4. Stepping into the control room during imaging runs.
5. Standing behind a full-length leaded shield.[41]
6. Increase the distance between the operator and the radiation source.
7. Placing movable lead shields between the operator and the X-ray beam when one cannot step away from the table.[42]
8. Redelineation of roles with the redistribution of responsibilities where possible.[41]

Conclusion

With the exponential rise in the use of IR procedures, it is essential to follow a holistic approach to limit radiation exposure to the operators and staff and to ensure improved patient safety. To ensure maximum radiation protection, it is paramount to understand the basics of radiation physics, understand its detrimental effects—deterministic and stochastic effects, learn to evaluate personal dosimetry data, and adhere to dose-limiting thresholds. Knowledge about various radiation protection equipment and good radiation safety practice is of utmost importance.

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References

1 Dehen L, Vilmer C, Humilière C, et al. Chronic radiodermatitis following cardiac catheterisation: a report of two cases and a brief review of the literature. Heart 1999;81(03):308–312
2 Nahass GT, Cornelius L. Fluoroscopy-induced radiodermatitis after transjugular intrahepatic portosystemic shunt. Am J Gastroenterol 1998;93(09):1546–1549
3 Vañó E, González L, Beneytez F, Moreno F. Lens injuries induced by occupational exposure in non-optimized interventional radiology laboratories. Br J Radiol 1998;71(847):728–733
4 Miller DL. Overview of contemporary interventional fluoroscopy procedures. Health Phys 2008;95(05):638–644
5 Valentin J. Annals of the ICRP Published on behalf of the International Commission on Radiological Protection [Internet]. 2007 [cited 2020 Jun 3]. Accessed November 20, 2021
6 Padovani R, Bernardi G, Quai E, et al. Retrospective evaluation of occurrence of skin injuries in interventional cardiac procedures. Radiat Prot Dosimetry 2005;117(1-3):247–250
7 Cutaneous Radiation Injury (CRI)|CDC Radiation Emergencies [Internet]. [cited 2020 Jun 3]. Accessed November 20, 2021 from: https://www.cdc.gov/nceh/radiation/emergencies/criphysicianfactsheet.htm
8 The 2007 Recommendations of the International Commission on Radiological Protection [Internet]. [cited 2020 Jun 3]. Accessed November 20, 2021 from: http://www.elsevier.com/wps/find/bookdescription.cws_home/713998/description#descriptionhttp://www.elsevier.com/wps/find/bookdescription.cws_home/714371/description#description
9 AVOIDANCE OF SERIOUS X-RAY-INDUCED SKIN INJURIES TO PATIENTS DURING FLUOROSCOPICALLY-GUIDED PROCEDURES [Internet]. [cited 2020 Jun 3]. Accessed November 20, 2021 from: https://www.fda.gov/media/74894/download
10 ACR-AAPM TECHNICAL STANDARD FOR MANAGEMENT OF THE USE OF RADIATION IN FLUOROSCOPIC PROCEDURES [Internet]. [cited 2020 June 3]. Accessed November 20, 2021 from: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/Mgmt-FluoroProc.pdf
11 Miller DL, Balter S, Dixon RG, et al; Society of Interventional Radiology Standards of Practice Committee. Quality improvement guidelines for recording patient radiation dose in the medical record for fluoroscopically guided procedures. J Vasc Interv Radiol 2012;23(01):11–18
12 Valentin J. Avoidance of radiation injuries from medical interventional procedures, ICRP Publication 85. Annals of the ICRP 2000; 30(02):7–7
13 Research LW-R 1994undefined. Limitation of Exposure to Ionizing Radiation. adsabs.harvard.edu [Internet]. [cited 2020 Jun 3]; Accessed November 20, 2021 from: http://adsabs.harvard.edu/abs/1994RadR.137.417W
14 Jung CH, Ryu JS, Baek SW, et al. Radiation exposure of the hand and chest during C-arm fluoroscopy-guided procedures. Korean J Pain 2013;26(01):51–56
15 Skripochnik E, Loh SA. Fluoroscopy time is not accurate as a surrogate for radiation exposure. Vascular 2017;25(05):466–471
16 Smythe WR. 2014Inverse-square law. In: AccessScience. McGraw-Hill Education. Doi: 10.1036/1097-8542.350600
17 Synowitz M, Kiwit J. Surgeon's radiation exposure during percutaneous vertebroplasty. J Neurosurg Spine 2006;4(02): 106–109
18 Whitby M, Martin CJ. Radiation doses to the legs of radiologists performing interventional procedures: are they a cause for concern? Br J Radiol 2003;76(905):321–327
19 Shortt CP, Al-Hashimi H, Malone L, Lee MJ. Staff radiation doses to the lower extremities in interventional radiology. Cardiovasc Intervent Radiol 2007;30(06):1206–1209
20 Thornton RH, Altamirano J, Dauer L. Abstract No. 134: Featured abstract. J Vasc Interv Radiol 2009;20:S52–S53
21 Maeder M, Brunner-La Rocca HP, Wolber T, et al. Impact of a lead glass screen on scatter radiation to eyes and hands in interventional cardiologists. Catheter Cardiovasc Interv 2006;67(01):18–23
22 Luchs JS, Rosioreanu A, Gregorius D, Venkataramanan N, Koehler V, Ortiz AO. Radiation safety during spine interventions. J Vasc Interv Radiol 2005;16(01):107–111
23 Kloeze C, Klompenhouwer EG, Brands PJM, van Sambeek MRHM, Cuypers PWM, Teijink JAW. Editor's choice–Use of disposable radiation-absorbing surgical drapes results in significant dose reduction during EVAR procedures. Eur J Vasc Endovasc Surg 2014;47(03):268–272
24 Dromi S, Wood BJ, Oberoi J, Neeman Z. Heavy metal pad shielding during fluoroscopic interventions. J Vasc Interv Radiol 2006;17 (07):1201–1206
25 King JN, Champlin AM, Kelsey CA, Tripp DA. Using a sterile disposable protective surgical drape for reduction of radiation exposure to interventionalists. AJR Am J Roentgenol 2002;178 (01):153–157
26 Bahreyni Toossi MT, Zare H, Bayani S, Esmaili S. Evaluation of the Effectiveness of the Lead Aprons and Thyroid Shields Worn by Cardiologists in Angiography Departments of Two Main General Hospitals in Mashhad, Iran. In: Journal of Nuclear Science and Technology. Taylor and Francis Ltd.; 2008:159–162
27 Pelz DM. Low back pain, lead aprons, and the angiographer. AJNR Am J Neuroradiol 2000;21(07):1364
28 Wagner LK. Minimizing risks for fluoroscopic X-rays: Bioeffects, Instrumentation, and Examination. A credentialing program. Med Phys 1998;25(02):258–259
29 Savage C, Seale TM IV, Shaw CJ, Angela BP, Marichal D, Rees CR. Evaluation of a suspended personal radiation protection system vs. conventional apron and shields in clinical interventional procedures. Open J Radiol 2013;3:143–151
30 Worgul BV, Kundiyev YI, Sergiyenko NM, et al. Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures. Radiat Res 2007;167(02):233–243
31 Klein BEK, Klein R, Linton KLP, Franke T. Diagnostic x-ray exposure and lens opacities: the Beaver Dam Eye Study. Am J Public Health 1993;83(04):588–590
32 Koukorava C, Farah J, Struelens L, et al. Efficiency of radiation protection equipment in interventional radiology: a systematic Monte Carlo study of eye lens and whole body doses. J Radiol Prot 2014;34(03):509–528
33 Koukorava C, Carinou E, Ferrari P, Krim S, Struelens L. Study of The Parameters Affecting Operator Doses in Interventional Radiology Using Monte Carlo simulations. In: Radiation Measurements. Pergamon; 2011:1216–1222
34 Sturchio GM, Newcomb RD, Molella R, Varkey P, Hagen PT, Schueler BA. Protective eyewear selection for interventional fluoroscopy. Health Phys 2013;104(02, Suppl 1):S11–S16
35 Hu P, Kong Y, Chen B, Liu Q, Zhuo W, Liu H. Shielding effect of lead glasses on radiologists' eye lens exposure in interventional procedures. Radiat Prot Dosimetry 2017;174(01):136–140
36 Uthoff H, Peña C, West J, Contreras F, Benenati JF, Katzen BT. Evaluation of novel disposable, light-weight radiation protection devices in an interventional radiology setting: a randomized controlled trial. AJR Am J Roentgenol 2013;200(04):915–920
37 Miller DL, Vañó E, Bartal G, et al; Cardiovascular and Interventional Radiology Society of Europe Society of Interventional Radiology. Occupational radiation protection in interventional radiology: a joint guideline of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology. J Vasc Interv Radiol 2010;21(05): 607–615
38 Dauer LT, Miller DL, Schueler B, et al; Society of Interventional Radiology Safety and Health Committee Cardiovascular and Interventional Radiological Society of Europe Standards of Practice Committee. Occupational radiation protection of pregnant or potentially pregnant workers

in IR: a joint guideline of the Society of Interventional Radiology and the Cardiovascular and Interventional Radiological Society of Europe. J Vasc Interv Radiol 2015;26(02):171–181
39 Wagner LK. Limitation of exposure to ionizing radiation. Radiat Res 1994;137:417
40 Faulkner K, Marshall NW. Personal monitoring of pregnant staff in diagnostic radiology. J Radiol Prot 1993;13:259
41 McCollough CH, Schueler BA, Atwell TD, et al. Radiation exposure and pregnancy: when should we be concerned? Radiographics 2007;27(04):909–917, discussion 917–918
42 National Council on Radiation Protection and Measurements. Radiation Dose Management for Fluoroscopically Guided Interventional Medical Procedures. National Council on Radiation Protection and Measurements (NCRP); 2010

