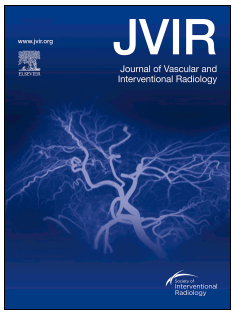

Occupational Protection in Interventional Radiology. A Joint Guideline of the Cardiovascular and Interventional Radiological Society of Europe and the Society of Interventional Radiology

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Occupational Protection in Interventional Radiology. A Joint Guideline of the Cardiovascular and Interventional Radiological Society of Europe and the Society of Interventional Radiology

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Supplementary Information

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Abstract

Purpose Since the initial edition of this Guideline was published in 2010, it has become increasingly clear that occupational protection involves more than just radiation protection. Additionally, radiation exposure to operators and staff occurs from sources other than fluoroscopy. This Guideline has been updated to incorporate these topics and to reflect new information on occupational protection in interventional radiology.

Methods The CIRSE Standards of Practice Committee, in conjunction with SIR, established a writing panel of twelve clinicians, medical physics experts, and others with internationally recognised expertise in occupational protection in interventional radiology. The writing panel identified regulations, guidelines, and radiation protection documents from international and national sources, including governments, radiation protection organizations, and professional associations. Additionally, the writing panel performed a pragmatic search on PubMed for relevant studies published in English between 2011 and 2025. The final recommendations were developed by consensus.

Results The revised Guideline provides advice and guidance to physicians, radiographers, nurses, medical physics experts, and all other staff involved in interventional radiology. It also includes an online-only Appendix with additional, in-depth coverage of several of the included topics.

Keywords Fluoroscopy - Computed tomography -Occupational protection - Ergonomics - Safety - Interventional radiology

Abbreviations

CIRSE	Cardiovascular and Interventional Society of Europe
D	Absorbed dose
E	Effective dose
EDE	Effective dose equivalent
FGI	Fluoroscopically guided interventional procedure
Gy	Gray
H	Equivalent dose
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IEC	International Electrotechnical Commission
MPD	Maximum permissible dose
NCRP	National Council on Radiation Protection and Measurements
PET	Positron emission tomography
PPE	Personal protective equipment
R	Roentgen
rem	Roentgen equivalent man
SIR	Society of Interventional Radiology
Sv	Sievert
VR	Virtual reality
w_T	Tissue weighting factor
Z	Atomic number

Introduction

Interventional radiology is the medical specialty that uses image-guided techniques to diagnose, treat, follow up, and palliate a broad range of pathologies [1]. Occupational protection is a necessity in interventional radiology. These procedures may involve high radiation doses and dose rates for patients and staff, as well as a risk of musculoskeletal injury to staff [2–6]. Occupational radiation exposure in interventional procedures is closely related to patient exposure, so occupational radiation protection should be managed in an integrated way with patient protection. However, measures to

protect staff must not impair the clinical outcome nor increase patient exposure [4, 7]. Occupational radiation protection requires the involvement of medical physics experts. Radiation protection measures must comply with local and national regulations and should consider the musculoskeletal detriment that can be caused by personal protective devices [4].

Radiation protection is necessary for all individuals working in the interventional radiology suite. This includes physicians, radiographers, and nurses [8–13], and individuals such as anesthesiologists who may be in a radiation environment only occasionally [14]. All these individuals may be considered radiation workers, depending on their level of radiation exposure and on national regulations. They require appropriate radiation dose monitoring, radiation protection tools and equipment, and education and training appropriate to their jobs [4, 15]. Their level of training should be based on the kind of work they do [15, 16].

Fluoroscopy is a major source of occupational radiation exposure in interventional radiology. It was addressed in the 2010 joint Cardiovascular and Interventional Society of Europe (CIRSE)—Society of Interventional Radiology (SIR) Guideline on Occupational Radiation Protection [7]. The current Guideline incorporates new information on occupational radiation protection and advice on other radiation sources, including CT guidance for procedures and radioembolization. It also provides a basic review of some relevant medical physics topics.

Since 2010 it has become increasingly clear that occupational protection involves more than just radiation protection. Interventional radiologists, like some other medical professionals, are at risk of developing chronic musculoskeletal injuries [6, 17–19]. These are discussed here. As with all operative procedures, there is also a risk of infection. This is not discussed here, as protection against infectious hazards is covered in detail elsewhere [20–23].

The goal of this Guideline is to provide advice and guidance to physicians, radiographers, nurses, medical physics experts, and all other staff involved in interventional radiology procedures. An online-only Appendix provides additional information on many of the topics discussed here.

This Guideline and Appendix use European terminology: radiographer (radiological technologist in the USA), and medical physics expert (medical physicist in the USA). Note also that in Europe a Radiation Protection Expert can be a nonmedical physics expert, as can a Radiation Safety Officer in the USA.

Methodology

The members of the Writing Panel are experts in interventional radiology and medical physics across a broad spectrum of interventional procedures from both the private and academic sectors of medicine. They identified regulations, guidelines, and radiation protection documents from international and national sources, including governments [24–29], radiation protection organizations [1, 4, 15, 16, 30–54], and professional associations [6, 7, 20, 21, 23, 55–65]. In addition, and as appropriate, a critical review of peer-reviewed articles was performed with regard to their study methodology, results, and conclusions. The qualitative weight of these guidelines and articles was evaluated and used to write the document, such that it contains evidence-based data. Agreement was reached on all statements in this document and the accompanying Appendix without the need for using consensus techniques.

The draft Guideline and Appendix were critically reviewed by the CIRSE Executive Committee and separately by the SIR Executive Committee. The Writing Panel discussed the comments from both Executive Committees, and appropriate revisions were made to create the finished draft. This draft underwent Cardiovascular and Interventional Radiology's standard peer review process. Appropriate revisions were made to create the finished document.

Musculoskeletal Injuries

Awareness and concern regarding musculoskeletal injuries has increased among interventional radiologists since 2010 [5, 19, 66–68]. These injuries are not unique to interventional radiologists—they also occur in other intervention alists and in surgeons [6, 17, 18, 57, 61, 68–71]. They can occur in any individual who works in an interventional laboratory and are even more common in radiographers and nurses than in physicians [72]. They can result in pain, lost time from work, and burnout [5, 71]. Specific factors associated with back pain in interventionalists include repetitive motion patterns, insufficient recovery time, prolonged standing, axial loading of the spine, and awkward body postures. A static, uninterrupted posture will increase the risk of long-term back pain through sustained isometric contraction of the lumbar extensor muscle group [18]. Cervical pain is associated with the use of poorly positioned ceiling-mounted monitors and the repetitive head and neck movements required to view these monitors while performing procedures [6].

SIR and others have published recommendations to help prevent these injuries [4–6, 17, 18, 57, 61, 66–70, 73–75]. Enhancing ergonomic practices in interventional radiology is essential [19]. Suggested measures to help prevent

musculoskeletal injuries are shown in Table 1 and discussed in detail in the Appendix.

Radiation Effects

The potential effects of radiation exposure on radiologists have been reviewed relatively recently [76–79]. Radiation exposure may result in two types of adverse biological outcomes: stochastic effects and tissue reactions. Stochastic caused by a mutation or other permanent change in a cell caused by a mutation or other permanent change in a cell that remains reproductively viable. The likelihood of a stochastic effect increases with dose (probably with no threshold, an assumption based on molecular knowledge of carcinogenesis) [51, 80]. Tissue reactions, formerly called deterministic effects, are caused by radiation-induced cell death or sterilization. They occur above a threshold radiation dose. Once the threshold is exceeded, there is a doserelated increase in severity.

Although the high levels of occupational exposure permitted before 1958 no longer occur [78], radiation-induced cancer remains the primary concern of most interventional radiology staff, as certain parts of organs and tissues (brain, lateral chest wall, and axillary portions of the breast) are not fully shielded and annual occupational exposures are generally higher for staff (particularly physicians) per-forming or assisting with interventional radiology procedures compared to most other medical radiation worker groups [13, 81, 82]. Radiation-induced cancer has been studied extensively [83]. Large, well-controlled observational cohort studies of occupationally exposed workers, including medical workers, with dosimetry data derived primarily from objective badge readings, have found modest associations between higher cumulative lifetime exposure to low-dose radiation and risks of death from solid cancers [84], including cancers of the breast [85] and lung [84, 86]. Stronger radiation dose-dependent associations have been observed with death due to leukemia [87, 88], but other high-quality studies found no association with leukemia incidence or death [89, 90]. Cohort studies have found no clear link between occupational radiation exposure and risk of malignant brain tumors, thyroid cancers, or other cancer outcomes [91–93]. For context, note that in the US population, approximately 40% of all individuals will develop cancer at some point in their life, and 20% of individuals will have cancer as their cause of death [94].

Table 1 Suggested measures to help prevent musculoskeletal injury in interventional radiology

Identify and stop performing activities that cause pain
Place the monitor in front of you at slightly below eye level [5, 6, 61]
Keep the monitor at a viewing distance that does not require you to bend forward to see image details
Adjust table height so that you do not need to bend over and your elbows are in a neutral position
Keep floor space clear to allow you to change positions during a case and to eliminate tripping hazards
Place the fluoroscopy pedal so that you do not need to move your body to reach it
Body positions that shift weight onto one leg should be avoided, even when using the foot pedal [18, 61]
Wear a lead apron that fits properly and provides only as much radiation protection as is needed
Use movable shields whenever possible to reduce the need for personal protective apparel
Avoid prolonged standing in one position
Avoid awkward body positions whenever possible
Take breaks of 1–2 min (‘‘microbreaks’’) every 20–60 min during a case [61, 69, 70]
Take breaks between cases whenever possible, to rest and stretch
Engage in physical fitness and conditioning programs to strengthen muscles and improve flexibility
Consider ergonomic issues when designing new fluoroscopy suites

Occupational radiation exposure in the interventional radiology suite may also be linked to cytogenetic changes (e.g., chromosomal aberrations) [79] and certain tissue reactions [35], including cataracts [95–97], cardiovascular effects [98], and neurologic effects [99]. These have been studied extensively as well [35, 49, 83]. High doses to the hands can occur when poor technique is used during administration of radioisotopes during radioembolization, during CT-guided interventions, or during fluoroscopy if the hands are placed in the direct beam. With CT fluoroscopy in particular, the annual dose limit for the hands can be reached after fewer than 10 procedures if the hands are kept in the beam [4, 100]. Individuals who routinely place their hands in the direct beam may violate local regulations [53] and are at risk of developing chronic tissue reactions. A more extensive discussion of stochastic effects and tissue reactions is provided in the Appendix.

Occupational Dosimetry

Dosimeter Use

Dosimeters worn by interventional radiology workers are typically collected and analyzed monthly to provide timely detection of elevated exposure levels and allow for prompt intervention and mitigation. Occupational dose information cannot be accurate unless dosimeters are worn routinely and correctly. Both single- and double-dosimeter protocols are in common use. Single-dosimeter measurements use one dosimeter, worn outside of protective apparel at the collar, to estimate whole-body and eye exposure. The two-dosimeter method adds a second dosimeter, worn inside protective apparel at the waist. The dose to the lens of the eye may be estimated from the collar dosimeter. The International Commission on Radiological Protection (ICRP) and National Council on Radiation Protection and Measurements (NCRP) recommend that interventionalists use the two-dosimeter method because the weighted average of the two readings provides a better estimate of whole-body exposure [4, 47]. More than half of the European countries that responded to a European Radiation Dosimetry Group survey have legal requirements about the number and position of dosimeters used for estimation of the effective dose when radiation protection garments are used [101]. In some countries, the required locations for the dosimeters differ from those in the standard two-dosimeter method. Local and national regulations for occupational dose monitoring must be followed, but with either method an additional badge may be worn if indicated. Additional dosimeters for the hands may be especially appropriate for specific procedures, such as radioembolization and CT fluoroscopy, but are of value for all procedures [4]. If doses to the collar dosimeter are expected to be high, an

additional dosimeter near the operator's eyes may be recommended. This is particularly useful when radioprotective eyewear is used, as estimates based on the collar dosimeter may overestimate dose to the lens of the eye. Additional information on dosimeters and dosimeter use is provided in the Appendix.

Table 2 Current dose limits (maximum permissible doses) for occupational exposure in Europe per 2013/59/Euratom [24] and the USA

Dose quantity	Region and dose limit
	Europe
Effective dose	
Annual	20 mSv/y averaged over five consecutive years (100 mSv in 5 years), with no single year exceeding 50 mSv
Equivalent dose	
Lens of the eye	20 mSv/y, averaged over defined periods of five years, with no single year exceeding 50 mSv
Skin[a]	500 mSv/y
Extremities (hands and feet)	500 mSv/y
Fetus	1 mSv for the entire pregnancy
	USA
EDE	
Annual	50 mSv/y
Cumulative	10 mSv x age (y)
Equivalent dose	
Lens of the eye	150 mSv/y
Skin[a]	500 mSv/y
Extremities (hands and feet)	500 mSv/y
Fetus	5 mSv over the duration of the pregnancy

EDE effective dose equivalent

[a]Averaged over 1 cm^2 of the most highly irradiated area of the skin

Adherence to institutional and regulatory standards is essential. ICRP Publications 60, 103, and 139 and NCRP Reports Nos. 122, 168, and 187 provide background information and guidelines specifically for managing occupational exposure methods [4, 30, 34, 43, 47, 52]. These reports recommend the use of dosimeters, regular monitoring, and strict adherence to dose limits. In interventional radiology facilities, optimal practice for occupational radiation protection includes the involvement of a Radiation Protection Expert or medical physics expert with knowledge of the practical aspects of interventional radiology and the fluoroscopes in clinical use.

Occupational Dose Limits

Effective dose (*E*) is intended to be proportional to the risk of radiation-induced detriment in health, principally from cancer. Occupational dose limits in Europe are included in Council Directive 2013/59/Euratom [24] and are based on ICRP recommendations [34, 35]. In the USA, effective dose equivalent (EDE) is used for these dose limits, which are also called Maximum Permissible Doses (MPD). The differences are described in the Appendix. Occupational dose limits for Europe and the USA are summarized in Table 2. Additional restrictions apply to the occupational exposure of pregnant workers. These are discussed below, in the section on Pregnancy.

Occupational dose limits for the lens of the eye have historically been based on the premise that cataract formation is observed only at high doses. The US Nuclear Regulatory Commission limit for lens exposure is 150 mSv/y and has not changed since 1991. In 2011, the ICRP recommended an annual equivalent dose limit for the lens of the eye of 20 mSv, with no single year exceeding 50 mSv, based on the assumption of a dose threshold of 500 mGy [35]. In 2016, the NCRP lowered its recommended dose limit for the lens of the eye from an effective dose of 150 mSv to an absorbed dose of 50 mGy, with the justification that the 50 mGy limit (as opposed to the 20 mSv limit recommended by the ICRP) is adequately protective and less restrictive for radiology practice [102]. However, in light of findings from epidemiologic studies over the last decade [95], others have suggested that even the lower ICRP recommended limits may be too lenient [103].

Occupational Doses in Interventional Radiology

A busy interventional radiologist who takes all appropriate radiation safety precautions is unlikely to exceed the 20 mSv ICRP limit for annual exposure. Several studies indicate that such an individual is more likely to have an *E* of 2–6 mSv/y [4, 9, 82, 104]. In France, all medical workers have shown a trend toward decreasing annual occupational dose [11]. In the UK, an overall downwards trend was also observed, with few physicians exceeding 6 mSv/y [14]. Although collar badge dose decreased in radiologists, there was an apparent increase in lens of the eye dose. The reason is not clear. This was not seen in a study of US medical staff performing or assisting with fluoroscopically guided interventional (FGI) procedures [81, 82]. Radiographers in the USA have a median annual dose <2 mSv, and are unlikely to exceed 10 mSv, with a trend to decreasing annual doses in recent years [13]. Nurses tend to have lower annual doses than radiographers, <1 mSv [9].

Personal Protective Equipment

Staff exposure in interventional radiology is mainly due to scattered radiation originating from the patient. Of the radiation emitted by the X-ray tube during fluoroscopic procedures, approximately 80% is absorbed by the patient's body, about 20% is scattered in different and random directions, and only 1% reaches the detector [105, 106]. The scatter field is highly asymmetric and is approximately 10 times more intense on the tube side of the patient than on the image receptor side [107]. Scatter distribution maps are provided in the documentation supplied with International Electrotechnical Commission (IEC) compliant fluoroscopes (essentially all fluoroscopes sold in the USA and Europe) [108]. Occupational radiation protection in fluoroscopy is achieved using a combination of personal protective equipment (PPE) that includes garments such as aprons, vests, skirts, thyroid shields, and eyewear; additional devices such as fluoroscope-mounted, rolling, or ceiling-suspended shields; and structural shielding incorporated into the walls, windows, and doors of the procedure room [109]. Additional information on PPE and radioprotective shields is provided in the Appendix.

PPE incorporates highly attenuating materials. These include lead or other high density, high atomic number (Z) materials [110]. For lead-free garments, the K-edge absorption characteristics of moderate Z materials are used, often in bilayers [111, 112]. Some countries no longer allow lead in PPE because lead must be managed as a hazardous material. Protective value is commonly stated in terms of ''lead equivalence,'' but transmission at specific radiation qualities is preferred because ''lead equivalence'' varies depending on scatter radiation quality [113]. At tube energies above 90 kV, lead-free materials are less protective than lead [110]. They may be adequate for protection during fluoroscopy but are less effective for protection during CT-guided procedures due to the higher kV used in CT. Typical

0.5 and 0.35 mm nominal thickness garments transmit 5% and 10% of fluoroscopic scatter. Unless national or local regulations specify a minimum lead or lead equivalent thickness, an appropriate thickness should be based on the wearer's under-apron dosimeter readings [4, 47]. Staff work habits and positioning should be accounted for when purchasing PPE. Some wraparound garments only provide the nominal protection where the two layers overlap. Ancillary staff who spend substantial time with their back to the patient should be aware of this. Garment weight is proportional to its protective value. Additional aspects of apron design and use are discussed under Musculoskeletal Injuries and Pregnancy in this Guideline and in the Appendix.

Radioprotective eyewear is necessary for those scrubbed in for interventional radiology procedures where ionizing radiation is used. These are available in a range of nominal lead thicknesses and anatomic coverage [4]. Radioprotective eyewear is also available for workers who need vision correction. To maximize protection, eyewear should have a large surface area, should extend laterally along the side of the face, and should fit tightly to the face [97, 114–116]. Eyewear needs to be comfortable, as it should be worn routinely. With appropriate design, eyewear with lower lead content can be both lighter and more effective than eyewear with a higher lead content [97, 116]. Work habits and positioning should also be accounted for, as turning one's head away from the patient toward display monitors can drastically increase radiation scattered to the eyes [114]. Radiation to other tissues in the head results in secondary scatter [117]. Protective eyewear cannot eliminate radiation dose to the lens of the eye from this secondary scatter. Use of ceiling-suspended shields is still necessary [118].

The cranium attenuates scattered radiation and reduces radiation dose to the brain by 40 to 50% [119, 120]. Radioprotective caps have been proposed to further reduce radiation exposure of the brain and the lens of the eye [119]. Caps that only cover the head above the level of the eyes do not protect against scattered radiation from the patient [64, 109, 121–124]. Some ''caps'' have ear flaps or extend to cover the head and neck, except for the face. These can provide some additional protection to the brain but may cause discomfort or interfere with hearing [121, 125].

Radioprotective surgical gloves and radioprotective creams are intended to protect the wearer's hands from scatter while the hands are outside the useful beam. For systems with automatic dose rate control, placing one's hand in the beam while wearing these gloves or creams increases both wearer and patient dose, as the system is attempting to penetrate two layers of leaded protection, while only a single layer is protecting the wearer [126].

Because approximately 70% of radiation-induced DNA damage is due to reactive oxygen species and free radicals created during X-ray irradiation, there is research interest in the use of oral antioxidants such as ascorbic acid, Nacetylcysteine, and beta carotene to prevent this damage [127–130]. Some protective effect on the DNA in circulating mononuclear cells has been observed in patients given oral antioxidants prior to nuclear medicine bone scans or cardiac catheterization, but results are mixed [127, 130]. Prophylactic dietary antioxidant supplementation does not appear to have been studied in health care workers regularly exposed to low doses of ionizing radiation.

Pregnancy

Pregnant radiation workers often worry about potential radiation risks to their unborn child. Inaccurate knowledge or misinformation can create a barrier for women who are considering careers in this field, possibly resulting in missed career opportunities. Radiation exposure during pregnancy does pose risks, including pregnancy loss, congenital malformations, developmental delay, and carcinogenesis, but these risks are extremely small with the use of appropriate radiation protection equipment and methods. These risks can be tissue effects (intrauterine growth retardation, miscarriage, and congenital defects) or stochastic effects (childhood cancer). The same risks occur in pregnancies where the embryo/fetus was never exposed to radiation (Table 3).

Biological effects on the fetus depend on the stage of pregnancy and the absorbed dose. The risks are greatest during organogenesis and the initial embryonic period in the first trimester of pregnancy, lower during the second trimester, and even lower in the third trimester [48]. The most critical period for the occurrence of tissue effects is between 8 and 15 weeks of gestation, when the radiation dose threshold is approximately 100 mGy [48, 58]. This is much higher than both regulatory limits and the expected level encountered by radiation workers using protective measures. Stochastic effects are thought to have no threshold dose, but the embryo/fetus is considered to have a similar risk for potential carcinogenic effects of radiation as an infant. Overall, there may be an extremely small increase in the probability of congenital

abnormalities or childhood cancer with occupational exposure within the expected dose to the fetus or embryo (Table 4) [31, 58, 131].

Radiation dose to the embryo/fetus is monitored for radiation workers using a dosimeter worn at waist level under any protective apparel. The dosimeter should be replaced monthly, starting when the worker declares her pregnancy. When two-dosimeter monitoring systems are used, the monitor worn under radiation protective garments should be placed at the waist level [48]. It is advisable to monitor radiation levels in a similar fashion when planning a pregnancy, to determine the likely embryo/fetus radiation dose for an individual's expected workload. Real-time dose monitoring during pregnancy can also be beneficial by offering regular updates on radiation dose levels.

Recent studies indicate that the occupational dose to the embryo/fetus of interventional radiology staff is well below 1 mSv. To date, there is no evidence in humans of congenital abnormalities at this level of dose [65]. Wunderle et al. evaluated fetal dose for the declared pregnancy for all declared pregnant workers in all imaging departments (including interventional radiology and interventional cardiology) over a 9-year period [132]. The average fetal dose was <0.3 mSv. Meek et al. found that the waist-level measurements for two pregnancies of one interventional radiology physician averaged 0.47 mSv for the entire 40 weeks of each pregnancy and 0.135 mSv for 10 pregnancies in 10 nonphysicians (maximum 0.38 mSv) [133]. Fetterly et al. reported a median under-apron abdomen measurement of 0.22 mSv (95th percentile 0.8 mSv) for a 40-week period collected from 42 interventional cardiology and electrophysiology physicians who wore 0.5 mm lead equivalent aprons [134]. Similarly, in a study involving an interventional radiology fellow who performed 280 neurointerventional procedures while wearing two 0.5 mm lead apron skirts, the radiation badge worn under the skirts recorded 0 mSv during the six months of declared pregnancy [135].

Table 3 Spontaneous pregnancy risks in the general population. Reprinted with permission from [58]

Type of risk	Spontaneous risk[a]
Risk of very early pregnancy loss (before first missed period)	~ 1 in 3
Risk of spontaneous abortion in known- pregnant women	~ 1 in 7
Risk of major congenital malformations	~ 1 in 33
Risk of severe mental disability	~ 1 in 200
Risk of childhood leukemia per year	~ 1 in 25,000
Risk of early-or late-onset genetic diseases	~ 1 in 10
Prematurity	~ 1 in 25
Growth retardation	~ 1 in 33
Stillborn	~ 1 in 50–250
Infertility	~ 1 in 15 couples

[a]Spontaneous risks facing an embryo at conception (i.e., at a 0 mGy radiation dose)

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Table 4 Probability of a live birth without malformation or without childhood cancer as a function of radiation dose. Reprinted with permission from [58]

Dose to embryo/fetus	No malformations (%)	No childhood cancer (%)	Neither (%)
0 mSv	96.00	99.93	95.93
0.5 mSv	95.999	99.926	95.928
1.0 mSv	95.998	99.921	95.922
2.5 mSv	95.995	99.908	95.91
5.0 mSv	95.99	99.89	95.88
10.0 mSv	95.98	99.84	95.83
50. mSv	95.90	99.51	95.43
100.0 mSv[a]	95.80	99.07	94.91

[a]For conceptus doses >100 mSv, consult a qualified medical physicist/medical physics expert for risk estimates

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Pregnant workers who desire additional radiation protection for their conceptus sometimes wear an additional lead apron or a maternity apron. This could decrease conceptus dose compared with a standard lead apron, but its additional weight may cause significant fatigue and strain during lengthy procedures [58]. It can also increase the potential for, or exacerbate, musculoskeletal and back pain, which is commonly encountered during a normal pregnancy even when no apron is worn.

In Europe, occupational radiation exposure during pregnancy is regulated by directives from the European Commission, which are reflected in national laws. European Directive 2013/59/Euratom mandates that after a worker has declared her pregnancy, the fetal dose should not exceed 1 mSv [24]. This aligns with ICRP recommendations [34]. The International Atomic Energy Agency (IAEA) states that ‘‘Notification of the employer by a female worker if she suspects that she is pregnant or if she is breast-feeding shall not be considered a reason to exclude the female worker from work’’

[37], but in some European countries (e.g., Austria, Hungary, Italy), occupational radiation exposure during pregnancy is not allowed [63]. In the USA, NCRP recommends a monthly dose limit of 0.5 mSv equivalent dose for the embryo/fetus after pregnancy is declared [50]. Moreover, pregnant radiation workers in the USA are not required to declare their pregnancy to their employer due to legislation and legal rulings meant to protect pregnant women from employment discrimination [29, 60]. This is in line with IAEA guidance that ‘‘a female worker cannot be compelled to notify her employer if she is aware or suspects that she is pregnant’’ [38].

In summary, legal requirements vary among countries, but pregnant interventional radiology physicians and staff can continue working safely during pregnancy if they follow appropriate radiation protection practices [64]. Medical physics experts should estimate the radiation dose to the conceptus for pregnant workers. Use of appropriate radiation protection equipment and methods should always result in exposure to the fetus well below the regulatory level. Termination of pregnancy because of fetal radiation exposure of < 100 mGy is not justified [48, 65], but this is rarely an issue because fetal doses should be less than 1 mGy, even with moderate to heavy workloads. Wearing protective garments with greater than 0.5 mm lead equivalent thickness provides no meaningful advantage for fetal radiation protection and increases the risk of musculoskeletal injury [64].

Practical Advice to Reduce or Minimize Occupational Radiation Dose

In general, decreasing patient dose results in a proportional decrease in scatter dose to the operator, making patient dose reduction beneficial for both patient and practitioner, creating a ‘‘win–win’’ scenario [4, 7]. Practical advice to reduce or minimize occupational radiation dose in specific interventional radiology settings is provided here and discussed more extensively in the Appendix.

Fluoroscopically Guided Procedures

Modern interventional fluoroscopy systems are extremely complex and highly sophisticated. Operators have both direct and indirect control over various factors that influence radiation dose as well as image quality. One of the most critical decisions an operator makes at the start of any procedure is selecting the appropriate imaging protocol on the fluoroscope. Optimizing these imaging protocols for specific clinical tasks or groups of tasks should be a collaborative effort among the clinical team, including an appropriately trained medical physics expert and a vendor imaging specialist.

The imaging protocol refers to the software exam type used during the procedure—denoted by some vendors as ‘‘organ programs’’ or ‘‘exam sets.’’ Modern systems offer imaging protocols with 100 or more individual parameters, each with multiple settings, resulting in a vast array of possible combinations. These settings influence key aspects such as the X-ray beam spectrum (which affects low contrast resolution and radiation dose rates), focal spot size selection (which affects high contrast resolution), and technical parameters that directly influence radiation dose rates, including default pulse rate, pulse width, spectral filtration, detector dose level, and maximum allowable dose rate (e.g., low, normal, or high fluoroscopy dose limits). The imaging protocol also determines the image processing applied to the acquired images, which must be appropriately tuned to the other parameters.

The operator is responsible for protecting others in the procedure room. In a randomized controlled trial, Komemushi et al. [8] showed that when nurses told the operator that they were going to approach the patient, the operator could avoid fluoroscopy while the nurse was close to the patient. This resulted in nurses having significantly lower occupational radiation doses, while operator doses were not significantly different. Additional parameters and techniques directly controlled by the operator are listed in Table 5 and described in more detail in the Appendix. This information has not changed over time [7, 32, 47, 136].

Radioembolization

In radioembolization procedures, microspheres containing a radioactive isotope are injected into hepatic artery branches to deliver localized, high doses of radiation to hepatic tumors. Currently, microspheres use ^{90}Y, a beta emitter. As of April 2025, ^{166}Ho, a beta and gamma emitter, is not available. Most of the radiation exposure to staff in radioembolization

procedures is from fluoroscopy. The radionuclide in use contributes only a small additional exposure during specific portions of the procedure. However, as discussed in the Appendix, the operator can receive high finger doses if appropriate protection measures are not used.

The most critical step in terms of occupational radiation exposure is microsphere injection. All vials containing ^{90}Y or ^{166}Ho activity, and all instruments and disposable items used for preparing the dose and implanting the device, should be handled with forceps and appropriate shielding to reduce finger doses. Due to the high-energy beta emission, shielding is best provided with a low atomic number material such as polymethylmethacrylate [4]. Double gloves are recommended to allow removal of a contaminated outer glove with a gloved hand. It is essential to flush all tubes and catheters with water or saline for injection before manual manipulation. Drescher et al. [137] showed that for ^{166}Ho administration, microsphere accumulation occurred at the three-way stopcock and the microcatheter hub. Disconnecting and reusing microcatheters for injection into a second or third location is a potential risk, so use of a new microcatheter may be desirable. In addition to all technical measures of radiological protection, training to speed up all steps of the procedure leads to a significant reduction of occupational exposure [4].

Table 5 Techniques to reduce occupational dose during fluoroscopically guided procedures

Obtain appropriate training
Use appropriate fluoroscopic imaging equipment
Use protective shielding
Wear your dosimeters and know your own dose
Use all available information to plan the interventional procedure
Use guidance tools (e.g., navigation systems, fluoroscopy overlays, vessel tracking) to help decrease procedure time and radiation for the procedure
Use available patient dose reduction technologies
Minimize fluoroscopy time
Minimize the number of radiographic images (e.g., digital subtraction angiography)
Use good imaging-chain geometry
Collimate
Position yourself in a low scatter area
Step out of the room during long radiographic acquisitions, especially cone-beam CT

CT-Guided Procedures

CT-guided interventions may be performed with intermittent CT, often referred to as ‘‘quick-check’’ or ‘‘step and shoot,’’ or CT fluoroscopy. For occupational protection, intermittent CT is preferable, as staff may step into the control area and benefit from structural shielding or stand in the shadow of the CT gantry [59]. With CT fluoroscopy, the need to manipulate instruments during CT scanning exposes the operator to relatively high levels of backscattered radiation. Fortunately, real-time CT fluoroscopy is not necessary for most CT-guided procedures [138]. Intermittent CT fluoroscopy is usually adequate. Use of this technique results in substantially decreased CT fluoroscopy times and radiation dose as compared to CT fluoroscopy and avoids direct exposure of the operator’s hand [138, 139].

Regardless of the method used, limiting the length of CT scans, using task-specific baseline technical factors, and adapting technical factors to patient size (e.g., using tube current modulation) will help optimize radiation doses to both the patient and the operator. The use of ultrasound as an adjunct or even as a replacement for CT is a further consideration. In many cases, prior information available from diagnostic imaging studies can be used to plan a CT-guided procedure, e.g., precisely define a limited preprocedure planning scan range. As shown in Table 6, there are many methods for limiting occupational exposure during CT-guided interventions [59, 100, 138–143]. Further discussion of these methods is provided in the Appendix.

Training

All individuals who participate in interventional radiology procedures need appropriate initial and periodic training [1, 15, 16, 25]. Here, ‘‘training’’ means the applied knowledge and practical aspects of radiation protection that result in improved efficiency and productivity. While education is related to theoretical knowledge, training is more practical and is usually conducted in a clinical environment [16, 144].

Safely delivering patient care in interventional radiology involves teamwork among individuals with a wide range of skill sets and professional backgrounds. Both patients and their health care teams are exposed to several risks relating to the delivery of these procedures. Appropriate training contributes to reducing patient and staff risks [145–147].

Table 6 Methods for limiting occupational exposure during CT-guided interventions

Avoid CT fluoroscopy; use the ‘‘quick-check’’ (‘‘step and shoot’’) CT imaging mode instead
Consider ultrasound as an adjunct or replacement for CT
Use information from previous imaging studies to plan the procedure and limit the scan range
Use task-specific baseline technical factors
Limit the length of helical scans
Step into the control room whenever possible during CT acquisitions
Stand in the shadow of the gantry during short CT acquisitions
Use mobile shields to provide additional protection for individuals who need to remain in the CT room during scanning
Use angular beam modulation during CT fluoroscopy, if available
If real-time CT fluoroscopy is necessary, stand as far as possible from the scan plane, use a long needle holder and a table-mounted lower body shield
Single-use sterile protective drapes may be useful but need to be placed close to, but not overlapping, the primary beam
Sterile radioprotective gloves offer limited protection at the beam energies used in CT
PET[a] radiation contributes only a small fraction to patient radiation doses and personnel exposure during PET/CT-guided procedures

[a]*PET* positron emission tomography

Effective radiation management is one part of a general safety culture [39], a concept that should be integrated into all radiation protection training [148, 149]. Real or potentially unsafe situations for patients and staff (not just radiation) can occur. Any individual who observes the situation should be able to communicate their concern appropriately to coworkers without fear of retaliation, intimidation, harassment, or discrimination. To ensure that the message is heard, the recipient should acknowledge and appropriately respond. All interventional radiology staff, including physicians, should be trained in this aspect of communication, which is an important part of a safety culture [39].

Member states of the European Union are required to promote and define radiation protection education and training for health professionals, but a recent survey showed uneven compliance [150]. This is not unique to Europe [40]. The ICRP, IAEA, European Commission, and NCRP recommend additional training elements for physicians who perform interventional procedures, beyond the level of training for other physicians [1, 15, 16, 25, 32]. Additional training is also needed for physicians who perform pediatric interventions due to the greater radiosensitivity of these patients compared to adults [15].

Some parts of radiation management training could incorporate virtual components, such as virtual laboratory exercises, simulators, and virtual reality (VR). Being able to ‘‘see’’ the radiation fields as the task progresses can provide a cognitive link between how a clinical task is performed and its radiation effects on both patients and staff. Students generally feel that they can recognize the clinical relevance of concepts taught via VR much more easily than those taught via lectures [151]. VR and simulation are discussed in more detail in the Appendix.

Education and training may be provided by individual facilities, outside academic institutions, health and regulatory agencies, professional bodies, equipment suppliers, freestanding training groups, or others [16]. Training content should be periodically reviewed and refreshed to ensure that it remains current. Accreditation of training suppliers and training content should be considered. This is required in some European countries. In this context, ‘‘accreditation’’ means that a training supplier has been approved by an appropriate body to provide education or training [16]. Additional information on training is provided in the Appendix.

Management Responsibilities

Administrators are unlikely to have a background in interventional radiology. Formal and informal training in interventional radiology, including a review of the risks to patients and workers, should be provided to these individuals.

Optimizing staff safety goals without compromising patient care is vital. Medical facilities should have a formal group whose task is to evaluate all risks to the facility, its patients, and workers. This group should have sufficient access to worker radiation safety experts to facilitate its responsibilities for worker risks in interventional radiology, including cataracts, radiogenic cancer, and the musculoskeletal risks associated with the use of personal radio protective devices. Current radiation protection devices and fluoroscopy suite design contribute to musculoskeletal injuries in interventional physicians, nurses, and radiographers [5, 17, 19, 57, 72]. It is possible to reduce risk to a reasonable level without using excessive resources [4, 152].

Worker radiation safety in interventional radiology is a responsibility of the designated health professional (‘‘Radiation Protection Expert’’ or ‘‘Radiation Protection Officer’’ in Europe, or ‘‘Radiation Safety Officer’’ in the USA). At some facilities in the USA, the Radiation Safety Officer’s responsibility is limited to oversight of radioactive materials. Medical physics experts may also have responsibilities for worker safety. Support from these individuals varies widely from the minimum of assuring regulatory compliance to full integration. All these individuals are more effective in optimizing safety if they have an appropriate understanding of the medical conduct of interventional procedures.

Glossary

Absorbed dose: the energy imparted to matter by ionizing radiation per unit mass of irradiated material at the point of interest. In the Systéme Internationale (SI), the unit is J kg^{-1} with the special name gray (Gy) [47].

Accreditation: with respect to radiation protection training, accreditation means that a training supplier has been approved by an appropriate body to provide education or training [16].

Cohort study: a research study that compares a particular outcome (such as lung cancer) in groups of individuals who are alike in many ways but differ by a certain characteristic, such as occupational radiation exposure. In a cohort study setting, random errors in estimates of dose tend to drive an association toward null (no effect) rather than to artificially inflate, or induce, an association.

Detriment: the total harm to health experienced by an exposed group and its descendants because of the group’s exposure to a radiation source. Detriment is a multidimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable nonfatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs [34].

Dose equivalent: a measure of the biological damage to living tissue as a result of radiation exposure. Also known as the ‘‘biological dose,’’, the dose equivalent is calculated as the product of absorbed dose in tissue multiplied by a quality factor and then sometimes multiplied by other necessary modifying factors at the location of interest. The dose equivalent is expressed numerically in rems or sieverts (Sv) [27].

Dose limit: the value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded [34]. The intent is to prevent the occurrence of radiation-induced tissue reactions or to limit the probability of radiation-related stochastic effects.

Effective dose: the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \text{ or } E = \sum_T w_T H_T$$

where $H_T \text{ or } w_R D_{T,R}$ is the equivalent dose in a tissue or organ, T, and w_T is the tissue weighting factor. The unit for effective dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv) [34]. Effective dose (E) applies only to stochastic effects.

Effective dose equivalent: the sum of the products of the dose equivalent to the organ or tissue $\left(H_T\right)$ and the weighting factors $\left(w_T\right)$ applicable to each of the body organs or tissues that are irradiated $\left(H_E = Rw_T H_T\right)$ [27].

Equivalent dose (H_T): the mean absorbed dose $\left(D_{T,R}\right)$ in a tissue or organ *T* weighted by the radiation weighting factor $\left(w_R\right)$ for the type and energy of radiation incident on the body:

$$H_T = \sum_R w_R D_{T,R}$$

The unit of organ equivalent dose is J kg^{-1} and has the special name sievert (Sv).

Excess relative risk: the rate of disease in an exposed population divided by the rate of disease in an unexposed population, minus 1.0. This is often expressed as the excess relative risk per Gy or per Sv [34]. (See also relative risk.) Fluoroscopically guided interventional procedure: an interventional diagnostic or therapeutic procedure per-formed via percutaneous or other access routes, usually with local anesthesia or intravenous sedation, which uses external ionizing radiation in the form of fluoroscopy to: localize or characterize a lesion, diagnostic site, or treat-ment site; monitor the procedure; and control and document therapy [47].

Gray: the special name for the SI unit of absorbed dose: 1 Gy = 1 J kg^{-1} [34].

***K*-edge**: the binding energy of the innermost electron shell (*K*-shell) of an atom. There is a marked increase in X-ray absorption of X-rays whose energy is just above the *K*-edge due to the photoelectric effect.

Interventional radiology: the medical specialty that uses image-guided techniques to diagnose, treat, follow up, and palliate a broad range of pathologies [1].

Maximum permissible dose: in the USA, a regulatory dose limit.

Occupational radiation exposure: radiation exposures to individuals that are incurred in the workplace because of situations that can reasonably be regarded as being the responsibility of management (radiation exposures associated with medical diagnosis of or treatment for the individual are excluded) [47].

Odds ratio: the ratio of the odds of an event occurring in the exposed group to the odds of the event occurring in the nonexposed group. It is commonly used in case–control studies where the incidence rates of the outcome are not directly measured, but given the outcome the odds of exposure can be calculated.

Operational quantities: quantities used in practical applications for monitoring and investigating situations involving external exposure. They are defined for measurements and assessment of doses in the body [34].

Personal protective equipment: garments and devices worn to protect against radiation exposures, such as aprons, thyroid shields, and leaded eyewear.

Posture: the spatial arrangements of body parts as they align to perform a task.

Rad: a unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/gram or 0.01 J/kg (0.01 Gy) [28].
For or X-rays and gamma rays, 1 rad = 1 rem = 10 mSv.

Relative risk: the ratio of the probability of an event occurring in the exposed group to the probability of the event occurring in the nonexposed group. It is typically used in cohort studies and randomized controlled trials, where the incidence of an outcome can be measured directly.

Rem (Roentgen equivalent man): a special unit of any of the quantities expressed as dose equivalent. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor (1 rem = 0.01 Sv) [28]. The quality factor for X-rays is 1.

Sievert: The special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram (J kg^{-1}).

Stochastic effect: Malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold [34].

Tissue reaction: Injury in populations of cells, characterized by a threshold dose and an increase in the severity of the reaction as the dose is increased further. Also termed tissue reaction. In some cases, tissue reactions are modifiable by postirradiation procedures including biological response modifiers [34]. These were previously called ‘‘deterministic effects.’’

Tissue weighting factor: the dimensionless factor by which equivalent dose is weighted to represent the relative contribution of that tissue or organ to the total radiation detriment resulting from uniform irradiation of the body. The w_Ts are judgment values grouped by organs and tissues in the interest of simplicity and rounded to sum to 1.0 [50].

Training: Applied knowledge and practical aspects of a topic that result in improved efficiency and productivity [16].

Uncertainty: Lack of sureness or confidence in predictions of models or results of measurements [50].

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Informed Consent For this type of study, informed consent is not required.

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Appendix: Occupational Protection in Interventional Radiology. A Joint Guideline of the Cardiovascular and Interventional Radiological Society of Europe and the Society of Interventional Radiology

Abbreviations, Acronyms and Symbols

Bq	Becquerel
CI	Confidence interval
CIRSE	Cardiovascular and Interventional Radiological Society of Europe
CNS	Central nervous system
D	Absorbed dose
DE	Dose equivalent
$d\bar{E}$	Mean energy imparted by ionizing radiation
dm	The unit mass of irradiated material
$D_{T,R}$	The absorbed dose in a tissue or organ
E	Effective dose
DMS	Dose management system
EDE	Effective dose equivalent
EPD	Electronic personal dosimeter
ERR	Excess relative risk
FGI	Fluoroscopically guided interventional procedure
FOV	Field of view
Gy	Gray
H	Equivalent dose
H_T	The equivalent dose in a tissue or organ
IAEA	International Atomic Energy Agency

ICRP	International Commission on Radiological Protection
IEC	International Electrotechnical Commission
$K_{a,r}$	Cumulative air kerma, also called reference air kerma
kVp	Peak kilovoltage
LNT	Linear-no-threshold
MPD	Maximum permissible dose
NCRP	National Council on Radiation Protection and Measurements
OR	Odds ratio
OSL	Optically stimulated luminescence dosimeter
PET	Positron emission tomography
P_{KA}	Air kerma area product, previously called dose area product
PPE	Personal protective equipment
R	Roentgen
Rem	Roentgen equivalent man
RR	Relative risk
SIR	Society of Interventional Radiology
Sv	Sievert
TLD	Thermoluminescent dosimeter
USRT	U.S. Radiologic Technologists Study
VR	Virtual reality
w_R	Radiation weighting factor
w_T	Tissue weighting factor

Introduction

This document accompanies the 2025 joint Guideline on Occupational Protection in Interventional Radiology of the Cardiovascular and Interventional Radiology Society of Europe (CIRSE) and the Society of Interventional Radiology (SIR) [1]. It contains additional information and more detailed reviews of some topics discussed in the Guideline, as well as additional medical physics topics that were not included in the Guideline.

Radiation Protection Quantities and Units, Personal Dosimetry, and Uncertainty

Quantities and Units

Absorbed dose (D) is a measurable radiation quantity defined as the mean energy ($d\bar{E}$) imparted by ionizing radiation per unit mass of irradiated material (dm) at the point of interest. The unit is J kg^{-1} with the special name gray (Gy) [2]:

$$D = \frac{d\bar{E}}{dm}$$

D is a measurable quantity from which derived quantities can be calculated. It is therefore often the starting point for occupational dosimetry. Numerous assumptions and corrections are applied to the dosimeter measurement to estimate the occupational dose experienced by the wearer.

Once D has been determined, two derived radiation quantities can be calculated—Equivalent Dose and Effective Dose. Both are expressed in sieverts (Sv). Multiplying D by a radiation weighting factor (w_R) to account for differences in the biological effects of various types of radiation for a given energy deposition yields Equivalent Dose (H). For diagnostic energy x-rays, w_R is 1, so D and H are the same.

The Equivalent Dose for each tissue or organ (H_T) is the mean absorbed dose in a tissue or organ ($D_{T,R}$) weighted by the radiation weighting factor (wR) for the type and energy of radiation incident on the body:

$$H_T = \sum_R w_R D_{T,R}$$

H_T can then be multiplied by a tissue weighting factor (w_T) for that organ or tissue to account for the biological differences in radiosensitivity of various organs and tissues. Summing these values over all organs and tissues allows for an overall estimate of risk, called Effective Dose (*E)*.

$$E = \sum_T w_T \sum_R w_R D_{T,R}$$

Or

$$E = \sum_T w_T H_T$$

E and *H* use the most recent weighting factors published by the International Commission on Radiological Protection (ICRP) in Report 103 [3]. Regulations in the U.S. have not incorporated these weighting factors and instead use older factors from ICRP Report 60 [4] that yield slightly different values and have different names: Effective Dose Equivalent (EDE) and Dose Equivalent (DE), that correspond to *E* and *H*, respectively.

Personal Dosimetry

A typical personal dosimeter is designed and calibrated to report two operational quantities: Hp(0.07) and Hp(10), where Hp is the personal equivalent dose. These represent the dose equivalent in soft tissue at 0.07 mm and 10 mm depth from the surface of the body, respectively, at the location of the dosimeter. Hp(0.07) from the collar dosimeter worn over protective garments (apron, thyroid shield) provides a reasonable estimate of the dose delivered to the surface of the unshielded skin and to the unshielded lens of the eye. Consultation with a medical physics expert is recommended if the collar dosimeter is used to estimate the dose to the lens of the eye, because the collar dosimeter value does not incorporate the effect of leaded eyewear. In Europe, Hp(10) from the dosimeter worn on the anterior chest

inside protective garments is assumed to be a good estimate of the operator's effective dose (*E*) and was previously considered an adequate indicator of the possible health detriment from radiation exposure. A single under-lead dosimeter does not provide any information about eye lens dose. The formula used to estimate *E* from dosimeter data may be specified by national regulations or by local hospital policy. In the United States, when a protective apron is worn during diagnostic and interventional medical procedures that use fluoroscopy, the National Council on Radiation Protection and Measurements (NCRP) recommends combining the Hp(10) values from both body and collar dosimeters to estimate *E*:

E (estimate) = 0.5 HW + 0.025 HN

where HW is the reading from the dosimeter at the waist or on the chest, under the protective apron, and HN is the reading from the dosimeter at the neck, outside the protective apron [5]. However, not all regulatory authorities allow this methodology. (In the U.S., the individual states regulate occupational protection from x-rays). When uncorrected dosimeter readings must be used, they likely substantially overestimate the *E* or EDE of the wearer.

Uncertainty

Accurate estimation of occupational radiation dose relies on the proper selection of dosimetry devices, adherence to the requirements and assumptions made by the dosimeter type, appropriate occupational monitoring policies and protocols, and strict compliance with all institutional and regulatory requirements. All discussions of measurement accuracy and uncertainty assume that these requirements are met; without them, uncertainties cannot be accurately estimated and could theoretically be infinite. This underscores the need for robust oversight and a vigilant safety culture to ensure that radiation dose is appropriately monitored.

Uncertainty in the context of occupational dosimetry is complex. There is uncertainty in measurement, as there is with any measured value. This is dependent on many technical factors but is generally considered to be in the 1-5% range [6]. This uncertainty increases as those measured data are then used to estimate organ doses to individuals with a wide range of body habitus, inconsistent

measurement locations, and varying irradiation conditions. Because of this uncertainty, the formulas used to derive *E* and EDE intentionally tend toward overestimation. This is desirable for radiation safety purposes but may unduly alarm individuals with high readings whose actual E or EDE is overestimated [5]. The assigned *E* or EDE for any individual must be considered with an understanding that the value is a crude estimate and likely substantially exceeds the actual doses received.

There is also considerable uncertainty in the application of risk estimates for single acute radiation exposures to the occupational situation of chronic exposure to low doses of ionizing radiation. This is not generally accounted for in occupational radiation exposure analyses and is not well understood in the context of occupational exposure.

Occupational Dosimetry

Dosimeters

Commonly used personal dosimeters include thermoluminescent dosimeters (TLDs), optically stimulated luminescence (OSL) dosimeters, and electronic personal dosimeters (EPDs). TLD and OSL devices are periodically analyzed to determine the dose that they receive. Some EPDs can provide real-time monitoring and display the results while a procedure is in progress. Although many technologies are available, all devices used for regulatory purposes should be appropriately accredited. In fluoroscopically guided interventional procedure (FGI) settings, dosimeters are typically collected and analyzed monthly to provide timely detection of elevated exposure levels, allowing for prompt intervention and mitigation.

Electronic personal dosimeters provide real-time monitoring and instant feedback, allowing for immediate corrective actions if necessary. They may provide audible dose-rate indications and visual displays of dose rates. They can be a valuable tool as part of radiation protection training for both fluoroscopy and CT-guided procedures but are not a substitute for practical radiation protection training [7-9]. EPDs work well in supervised training situations but may be distracting or ignored when routinely

deployed. They are typically worn over protective apparel. If they are used for regulatory purposes, they should be accredited for that purpose. In some cases, if a dose management system is available, it is possible to link occupational and patient doses to compare operator practices and optimize occupational radiation protection strategies [10].

The ICRP also recommends the use of an "ambient dosimeter" located on the C-arm (**Figure 1**), to measure the level of scatter dose that would be received if protective apparel were not used [11]. These dosimeters provide backup to personal dosimetry and can be used to assess scatter radiation fields on a continuing basis, demonstrate non-compliance in wearing personal dosimeters, help estimate occupational doses when personal dosimeters have not been worn, integrate occupational and patient protection, and help in optimization of individual radiation protection habits [11-13]. If there is appropriate use of radiation protection tools (e.g., ceiling-suspended shields), measured occupational doses per procedure should be only a few percent of the value measured by the ambient dosimeter [14].

Dosimeter Use

The ICRP and NCRP recommend that interventionalists use the two-dosimeter method because the weighted average of the two readings provides a better estimate of whole-body exposure [11, 15]. In 14 of 26 European countries there is a legal requirement to estimate the dose to the lens of the eye [16]. The dose to the lens of the eye may be estimated from the collar dosimeter. The two-dosimeter method also has the advantage that the waist badge can be used to monitor fetal dose during pregnancy. This method is common practice in Europe, where it is frequently required by national regulation. In some countries, monitoring of hand dose is mandatory.

Both the single dosimeter and two-dosimeter methods have disadvantages. If the single dosimeter is worn over the apron, it is not possible to estimate whole body exposure because there is no way to determine the protective effect of the apron, or if an apron is even worn. If the dosimeter is worn under the apron, as is the practice in some countries, the dosimeter cannot be used to estimate the dose to the

lens of the eye. With the two-dosimeter method, if the dosimeters are switched, the whole-body value can be overestimated by up to a factor of 10. When worn correctly, the two-dosimeter method may overestimate whole-body dose for U.S. workers by nearly a factor of 3 due to the formula used to calculate EDE [17]. The two-dosimeter method is also more expensive. In the United States most states require only a single dosimeter [18], so the two-dosimeter method is less commonly used, primarily because staff often wear their dosimeters incorrectly [17, 19, 20]. Use of the two-dosimeter method in the U.S. has declined over time [17].

Evaluation of Personal Dosimetry Data

Personal dose records should contain the information required by regulation and the dose values measured by all personal dosimeters used by individuals involved in interventional radiology. They should be reviewed regularly by a medical physics expert or radiation protection expert, with results communicated to users as required by regulation or facility policies. Dose values should be reviewed as required by local regulations (in the U.S., at least quarterly) with results reported to individuals at least annually. Aggregate dosimetry results can be reported to department leaders who should be familiar with the workloads of the badged personnel.

Review of dosimetry records should ensure that annual dose limits are not exceeded and that reported values are consistent with those expected from that worker's duties. Abnormally high or low values should be investigated, even if the user is unlikely to exceed annual exposure limits. Normalization of occupational doses by number of cases or by metrics such as total P_{KA} or total $K_{a,r}$ may be possible, and is useful for comparing occupational exposure between cohorts with varying caseloads.

The ICRP recommends that "There is no need to wait until an annual dose limit or constraint has been exceeded to become aware that protection was not optimized. Non-optimized protection can be

detected by establishing an investigation level" [11]. Because badge readings for interventional operators are expected to be higher than for most other hospital workers, their investigation levels should be set to avoid non-productive investigations of otherwise expected exposure levels. ICRP publication 103 recommends against setting triggers as arbitrary fractions of the dose limit [3]. The World Health Organization recommends investigation when monthly exposure reaches 0.5 mSv for effective dose, 5 mSv for dose to the lens of the eye, or 15 mSv to the hands or extremities [21].

Typical staff dose readings for different types of procedures have been published in the literature. Depending on the type of procedure and the technique used, median operator effective dose, per procedure, ranges from 1.6 to 33 μSv [22, 23]. As noted in the guideline, a busy interventional radiologist who takes all appropriate radiation safety precautions is unlikely to exceed the 20 mSv ICRP limit for annual exposure and more likely to have an *E* of 2–6 mSv/y [11, 24, 25].

When professionals have very low doses in comparison with other staff doing similar work, proper use (or lack of use) of personal dosimeters should be investigated. Abnormally high doses should also be evaluated. Investigation of abnormally high or low personal dose value begins with a check of the validity of the dosimeter reading. Potential sources of invalid dosimeter readings include not wearing dosimeters at all, improper badge positioning (including mixing up over- and under-apron badges), and storage of badges on protective equipment such as aprons or thyroid collars within the fluoroscopy suite.

Sources of valid but elevated readings include increased operator caseload, fluoroscope protocol modification, initiation of new, more complex procedures, and poor radiation safety practices such as failure to utilize available shielding or inappropriate use of high dose protocols or modes of operation. Operator caseloads can often be extracted from dose monitoring software or electronic medical records for ready comparison. If the abnormal doses are observed for several professionals, the results of the quality control analysis of the X-ray system should also be investigated. If an invalid reading is suspected, the reading for the individual's next monitoring period should be reviewed to ensure the problem has been corrected. If it has, the invalid reading can be replaced with an average monthly exposure in the dose record.

When a seemingly valid elevated reading is encountered, the worker should be notified and asked if there was a change in work habits that could explain the increase in radiation exposure. Was a new type of procedure initiated during the monitoring period? Were procedure techniques or equipment settings modified? If so, did these new methods require remaining in closer proximity to the patient or increased patient dose? Did procedure workload or complexity increase? Sometimes, a temporary cause is found. If this is the case, dose levels should return to usual levels during the next monitoring period, when workload returns to normal, equipment settings are corrected, or there is additional experience with a new procedure or technique. The individual's dose reading for the next monitoring period should be reviewed to confirm that dose levels have returned to the expected range.

For legitimately high dose readings with no obvious cause, operator working habits may be observed by a medical physics expert or interventional physician with knowledge of radiation protection principles and the operation of the specific equipment being used. Attention should be paid to equipment settings such as pulse rate and mode of operation, the worker's proximity to the patient, the use of collimation, and the use of equipment-mounted shields and protective equipment. When available, real-time dosimeters are useful for visualizing the radiation protection effects of these elements of practice. With adequate cooperation and attention to dose reduction principles, forced limitation of workload to ensure compliance with dose limit is generally not needed.

Radiation Effects

The earliest experimenters with x-rays shielded neither the x-ray tube nor themselves. Some developed cancer as a result [26, 27]. Others developed chronic dermatitis [28]. Radiologists practicing in the 1940s and 1950s could receive occupational radiation doses far higher than those permitted today [29]. In 1936, the recommendation for a permissible whole body occupational exposure was 0.1 R/day (1

mSv/day) [30]. It decreased in the U.S. to the current occupational limit of 50 mSv/y (5 rem/y) only in 1958 [28]. The ICRP established a recommended whole body occupational dose limit of 20 mSv/y, averaged over 5 years, in Publication 60, published in 1991 [4].

Much of what we know about the risk of radiation exposure in humans comes from epidemiologic studies. Analysis of risk per unit organ dose ("dose-response") is the preferred modeling approach used in these studies [31], with results reported in terms of the excess relative risk (ERR) per unit dose (e.g., Gy or Sv). Organ doses are more appropriate for use in dose-response assessment than effective doses because they are more biologically meaningful. Dose-response analyses are more statistically powerful than those that use categorical or binary comparisons (e.g., relative risks (RRs) or odds ratios (ORs) comparing exposed versus unexposed) because they use data from the entire dose range and are less prone to exposure misclassification and confounding. Dose-response analyses are also preferred to an approach that relies on surrogate exposures (e.g., number of times exposed, distance from radiation source, number of years worked, number of medical procedures performed).

Organ dose reconstruction for radiation epidemiologic studies has become increasingly sophisticated, but uncertainties around organ dose estimates can be quite large and can hinder the interpretation of epidemiologic studies. Uncertainties are not necessarily higher at lower doses, but they can make it more difficult to "detect" a significant association at low doses [32, 33]. Furthermore, in a cohort study setting, random errors in estimates of dose tend to drive an association toward null (no effect) rather than to artificially inflate, or induce, an association [32]. Therefore, it is unlikely that inaccuracies in dose reconstruction can "explain away" a statistically significant positive dose-response association.

Findings from epidemiologic studies of occupationally exposed workers are described below. There are important considerations when interpreting these findings. First, occupationally exposed workers tend to be healthier, on average, than the general population and have lower age-adjusted mortality rates. To minimize such biases, the most valid assessments of risk in cohort studies tend to be those conducted using internal comparisons (i.e., among the study subjects rather than with an external

group such as the general population) with statistical adjustment for potential confounding factors, such as cigarette smoking. Second, the absolute risks (i.e., number of excess events) of cancer, circulatory, and neurological outcomes attributable to occupational radiation exposure are estimated to be very small. For instance, a survey of medical workers in interventional radiology departments in South Korea estimated a lifetime excess risk of cancer attributable to occupational radiation exposure of 338, 121, and 156 per 100,000 male radiologists, male radiologic radiographers, and female nurses, respectively [34]. On the other hand, estimates of relative risk (as described below) may be substantially underestimated, thus yielding an underestimate of the absolute risk. Third, results of studies of monitored workers generally do not account for lack of compliance in the use of dosimeters. Unfortunately, this is common, particularly among interventionalists [17, 25, 35-37], and would lead to attenuation in the estimated risks. Also, medical worker cohorts generally report high and consistent use of lead aprons and room shields, particularly in interventional radiology departments [38]. In settings where the use of personal protective equipment is low, the risks of cancer and other radiation-associated outcomes may be much higher.

Cancer Risks

Ionizing radiation is one of the most well-studied carcinogens and is an established cause of nearly all types of cancer [31]. In epidemiologic studies with high-quality organ dose reconstruction, risks of most type of cancer tend to increase linearly across the full range of dose [39], with no clear evidence to date of a dose threshold (i.e., level of dose below which there is no risk) [40]. This is the basis for adoption of the "linear-no-threshold" (LNT) model by national and international scientific committees as the most pragmatic and prudent model for radiation protection purposes [3, 41-43].

Our current understanding of cancer risks associated with protracted (repeated) low-dose radiation exposures has been derived primarily from studies of acute (one-time) exposures. The Life Span Study includes about 120,000 Japanese atomic bomb survivors identified 5-10 years after the 1945 bombings of Hiroshima and Nagasaki. It is widely regarded as the "gold standard" of radiation epidemiology research and has been the source of many comprehensive reports of radiation-related risks

of total and specific types of solid cancers and hematologic malignancies [44]. Results from this study indicate that adult radiation exposures are most strongly associated with cancers of the bladder, female breast, lung, and brain and central nervous system, as well as leukemia (excluding chronic lymphocytic leukemia) [31].

In recent years, large cohort studies and pooled analyses of occupationally exposed medical and nuclear workers and patients undergoing imaging procedures have contributed more direct information about the health effects of repeated (protracted) exposure to low-dose radiation. In general, these studies have not found much of a difference in risks of cancer (and some non-cancer outcomes) between cumulative dose spread out over time versus the same dose received all at once [45-49].

In the U.S., it is expected that approximately 40% of all individuals will develop cancer at some point in their life, and 20% of individuals will have cancer as their cause of death, as shown in **Table 1** [50]. In a large multinational cohort study of nuclear workers monitored with personal dosimeters, higher occupational organ/tissue-absorbed radiation dose was associated with a modest increased risk of death due to solid cancer overall and lung cancer specifically [49], as well as a relatively stronger increase in risk of death due to leukemia (not including chronic lymphocytic leukemia) [47]. In the U.S. Radiologic Technologists Study (USRT), occupational organ/tissue-absorbed radiation dose, derived primarily from objective badge records, was positively associated with female breast cancer incidence and mortality and lung cancer mortality (particularly in radiographers with <20 pack-years of smoking history) [51, 52]. However, no clear dose-response associations were observed for leukemia or cancers of the skin, brain/central nervous system, or thyroid [53-56]. Similar null dose-dependent findings for brain/central nervous system cancer, thyroid cancer, and leukemia were observed in the French and South Korean medical worker cohorts, although the follow-up duration and number of events in these cohorts were much more limited compared to the USRT cohort [57-59].

Overall cancer mortality rates in a large cohort of U.S. male physicians who specialized in interventional radiology, interventional cardiology, or interventional neuroradiology were significantly lower compared to rates in an unexposed comparison group (psychiatrists). A non-significant increased

rate of leukemia mortality was observed among interventionalists who graduated from medical school before 1940, who likely received the highest lifetime exposures [60]. The number of female physicians was too small to draw any conclusions about mortality risks for this group, so an increased risk of death from female-specific cancers, including female breast cancer, could not be excluded. Also, the follow-up of this cohort was relatively short, and the average age of the physicians at the end of follow-up was only 51 years, so additional follow-up will be required. A recent case-control study found no association between the number of ionizing radiation procedures performed and the risk of cancer among physicians in Ontario, Canada, over a 30-year period (1991-2021) [61]. Results from selected large worker cohorts are shown in **Table 2.**

Case series have raised concerns about the risks of brain and central nervous system tumors in physicians who perform FGI procedures, including a higher frequency of left-sided versus right-sided brain tumors, consistent with generally higher occupational exposure on the left side [62, 63]. Such reports are difficult to interpret due to the lack of an unexposed comparison group. While there is a lack of convincing evidence linking occupational radiation exposure and malignant brain/CNS tumors, an elevated risk for benign brain/CNS tumors would be consistent with findings from the Japanese Life Span Study and thus cannot be ruled out [31]. Estimates of radiation-associated risks of benign brain/CNS tumors from occupational cohort studies are forthcoming.

Lens Opacities

Radiation-induced cataracts have been observed in health care workers, including those who participate in FGI procedures, as well as several other radiation-exposed populations [64-74]. A systematic review of the health effects of occupational exposure to ionizing radiation found that the occurrence of lens opacities among interventionalists varied significantly, from 16% to 47% [75]. Results from selected large worker cohorts are shown in **Table 3**. In general, posterior subcapsular and cortical cataracts have been more consistently linked with radiation exposure, although there is some limited evidence of an association with the nuclear type. The large USRT cohort demonstrated a linear dose-

dependent relationship between occupational radiation exposure and self-reported diagnosis of cataract, with a significant increased risk at radiation doses to the lens of the eye <100 mGy and no evidence of a threshold (i.e., dose below which there is no risk) [74]. A positive but non-significant association was observed after the analysis was restricted to surgically removed cataracts. In the same cohort, radiographers who reported regularly assisting with FGI procedures had an 18% higher risk of cataract during the follow-up period compared to those who did not. This risk increased with the frequency of procedures performed, particularly those performed while standing within three feet (1 m) of the patient [65], and was only observed among radiographers who did not consistently (>50% of the time) use room shields or lead glasses. This cohort was also studied for the risk of glaucoma and macular degeneration [76].

Several relatively small studies compared the prevalence of lens opacities based on a clinical eye examination, use of personal protective equipment, and sometimes occupational doses, between interventional cardiologists and an unexposed physician comparison group. A French study of 106 interventional cardiologists and 99 unexposed physicians found no difference in the prevalence of lens opacities overall, with a slightly higher proportion of posterior subcapsular lens opacities in the exposed group [66]. The risk increased with duration of activity but not workload and appeared to be lower with regular use of lead glasses. In a Finnish study of 21 radiation-exposed and 16 unexposed physicians, cumulative occupational exposure was not clearly associated with lens opacities of any type, based on ophthalmological examinations, nor were differences observed for the left versus right eye [67]. A similar study conducted in Germany compared interventional cardiologists and unexposed physicians, with a higher proportion of lens opacifications observed in the exposed group [68]. Interestingly, 68% of the participating interventional cardiologists reported never wearing lead glasses, while about 80% reported using ceiling-suspended and table shields and >90% reported using a lead apron and/or thyroid collar. In a study of 116 South American interventional cardiologists, nurses, and radiographers, the cardiologists had a 3.2-fold higher prevalence of posterior lens opacification compared to 93 age-matched unexposed individuals, while nurses and radiographers had 1.7-fold higher prevalence [69]. Cumulative median

values of lens doses were estimated at 6.0 Sv for cardiologists and 1.5 Sv for nurses and radiographers. The small sample size and low participation rates in these and similar studies conducted elsewhere make it difficult to draw firm conclusions. However, they are generally consistent in demonstrating evidence of radiation-induced lens opacities [70-72].

Between 2011 and 2014, a survey was administered to attendees of annual Italian interventional cardiology and electrophysiology conferences and at a local research facility, capturing medical history, work history, and lifestyle-related factors [73]. The study found that workers, particularly physicians, performing fluoroscopically guided cardiovascular procedures had a higher prevalence of several potentially radiation-related health issues, including cataracts, cancer, orthopedic issues, and anxiety/depression, than unexposed subjects.

Cardiac and Neurologic Outcomes

The effects of high-dose radiation exposures on cardiac and neurologic outcomes (including cognitive function) have been demonstrated clearly in experimental and epidemiologic studies. There is increasing evidence that links repeated low-dose radiation exposure with cardiac and neurologic tissue reactions [48, 77]. A small number of studies have suggested lower memory and olfactory performance, higher level of oxidative stress, and reduced glutathione in interventional cardiology versus unexposed medical staff [62]. The risk estimates for cardiac and neurologic outcomes vary, likely because the risk of a cardiac or neurologic outcome for a given absorbed dose is potentially less than that for cancer or cataract development. Also, risk estimates for cardiac and neurologic outcomes are more susceptible to confounding and the other types of bias inherent in observational cohort studies.

The results of analyses of large, occupationally exposed radiation cohorts for the risks of cardiovascular and neurologic outcomes are summarized in **Table 3** [60, 78-82]. In the large INWORKS cohort, which includes >300,000 nuclear workers monitored with personal dosimeters, a significant positive association was observed for cumulative radiation organ/tissue absorbed dose and circulatory

disease mortality [78]. In a cohort of >50,000 South Korean male diagnostic medical radiation workers, positive linear dose-response associations for cardiovascular disease, ischemic heart disease, and cerebrovascular disease were observed, based on organ/tissue absorbed doses derived from personal dosimeter readings. These estimates were not significant but were based on a relatively short follow-up period and a much smaller number of mortality events than the INWORKS study [79]. Dose-response estimates from the USRT cohort of radiologic technologists (who, like the INWORKS and South Korean cohort members, were also monitored with personal dosimeters) on radiation exposure and circulatory disease have not yet been published. However, after adjusting for age, birth year, gender, race, smoking history, and body mass index, analysis of the USRT cohort has shown that subjects who began working as radiographers in earlier calendar years, and those who worked as radiographers for more than five years before 1950 (when permitted occupational exposures were much higher than today) had a higher risk of death from ischemic heart disease and cerebrovascular disease than those who began working more recently [83]. Radiographers who reported working at least monthly with FGI procedures experienced a higher incidence of cerebrovascular disease compared to those who never worked with these procedures [84].

A large cohort study of U.S. male physicians who specialized in interventional radiology, interventional cardiology, or interventional neuroradiology found lower rates of death from cardiovascular and neurological and mental causes compared to unexposed physicians [60]. The number of exposed female physicians was too small to draw any definitive conclusions. The follow-up of this cohort was relatively short, and the average age of the physicians at the end of follow-up was only 51 years; additional follow-up will be required.

A meta-analysis of six occupational groups (totaling 517,608 workers) within the Million Person Study, comprising about 50% of the cohort, found an overall positive association between estimated cumulative radiation dose to the brain and death due to Parkinson's disease [80]. This finding is consistent with a study of workers in a Russian nuclear production facility [81]. However, in a French

nuclear worker study, no association was observed for Parkinson's disease mortality, but occupational exposure was significantly positively associated with dementia/Alzheimer's disease mortality [82].

Musculoskeletal Injuries and Prevention

In a survey of SIR members, musculoskeletal symptoms were reported by 88% of respondents. Fifty-eight per cent of those reporting these symptoms ascribed them to work-related activities [85]. Other surveys also demonstrate that large numbers of interventional radiologists (and interventional cardiologists and surgeons) report neck, thoracic or back pain [86-88]. Compared to the general population, interventional radiologists exhibit 1-year prevalence rates at the high end of the range for shoulder and low back symptoms and double the mean for neck symptoms [85]. These symptoms may result in time lost from work, leaves of absence, practice restriction, burnout, and early retirement [86, 89, 90].

Some individuals are particularly susceptible to developing musculoskeletal injuries. In a survey of staff who work in interventional radiology and interventional cardiology units at Mayo Clinic affiliated hospitals, Orme et al. found that factors associated with musculoskeletal pain in these workers were female sex, increasing time participating in interventional procedures, and increasing time wearing lead aprons [91]. In a survey of SIR members, Morrison et al. identified female gender, above-normal body mass index, and a practice length of 10 years or more as factors associated with a higher risk of moderate-to-severe symptoms [85]. In a survey of medical radiation workers in China, Li et al. identified female gender, alcohol consumption, repetitive motions, working overtime, and prolonged maintenance of the same posture as risk factors for neck, shoulder, and back work-related musculoskeletal injuries [92]. They also identified specific risk factors associated with back pain among interventional radiologists: repetitive motion, inadequate recovery time, prolonged standing, axial loading on the spine, and awkward postures.

Female gender is also associated with a higher frequency of musculoskeletal symptoms in surgeons, especially neck and upper extremity pain [86].

Posture is defined as the spatial arrangements of body parts as they align to perform a task [87]. Incorrect posture can lead to fatigue, discomfort, stiffness, and numbness in the back, neck, shoulder, and legs, as well as long-term disability or the need for corrective surgery [93]. The body should be kept in a neutral stance to alleviate tension in the torso and extremities. Procedure rooms should be designed to foster proper ergonomic positioning of the equipment with respect to the operator and patient to decrease the risk of posture-related and repetitive-stress injuries [86, 89, 94-96]. Fluoroscopes and other imaging equipment should be positioned to allow the operator to stand comfortably, without bending, leaning, or reaching.

Table height should be adjusted so that the operator does not need to bend over and so that the elbows can be held in a neutral position [97]. Positioning the table properly allows the biceps muscle to remain at less than 15% of maximum muscle activity while reducing back, shoulder, and wrist discomfort [89, 98]. Inappropriate table height can also cause sustained shoulder abduction, which results in deltoid muscle fatigue and deterioration in the performance of tasks requiring high accuracy [99]. It is important to avoid excessive or sustained shoulder abduction and internal rotation, a position that requires the greatest workload from the deltoid and trapezius muscles [87].

The monitor that displays fluoroscopy and reference images and physiologic data should be in front of the operator and just below eye level, to avoid unnecessary extension and rotation of the cervical spine [87, 89, 93, 94]. The fluoroscopy suite should be designed so that this monitor position is possible for all the positions around the procedure table where the operator is likely to work, including the patient's neck, arm, abdomen, groin, and foot. This may require additional monitors.

The fluoroscopic monitor's distance from the operator should be optimized. The goal is an upright posture with the spine in neutral position and without any forward tilt [87]. Viewing distance affects the eye's ability to extract details from an image. The optimum viewing distance depends on the combination of field-of-view (FOV), the size of the monitor, the area of the monitor occupied by the

image and the monitor pixel size [100]. For a fixed FOV, optimum viewing distance increases with increased monitor size. Interventionalists often lean over the patient to improve their ability to see detail in displayed images (**Figure 2**). With larger monitors, operators can stand further from the monitor and are more likely to assume a neutral spine position.

Spending long periods of time in a constant position, particularly an awkward position, should be avoided [87, 89]. Taking a break between cases can interrupt the cycle of pain [94]. Taking 1-2 min "microbreaks" every 20 to 60 min during a case has been shown to improve mental focus and physical performance and should be considered [86, 87, 89, 93]. Recommended stretching exercises can be performed during these breaks [93]. Hallbeck et al. [101] studied the effect of microbreaks with exercises in a group of 56 surgeons. The standardized exercises, described in the paper, took 1.5 to 2 min to perform and focused on the neck, back, shoulders, hands, and lower extremities. Of the 56 surgeons, 57% reported improved physical performance with use of microbreaks, 43% reported no change, and none reported decreased performance. There was no significant change in operative time. Impact on operative flow was minimal. At the conclusion of the study, 87% of participants wanted to incorporate microbreaks with exercises into their operative routine [101]. Park et al. [102] reported very similar results but may have been studying the same group of surgeons.

While most attention has been paid to ergonomic issues in the fluoroscopy suite, musculoskeletal injuries may also result from the awkward positions that can be necessary to perform CT, ultrasound-guided, and in-bore MRI-guided interventions [89, 103]. During CT interventions, the operator must often lean over the patient or bend to perform procedures, especially when CT fluoroscopy is used. The CT monitor in the room should be positioned to minimize unnecessary extension and rotation of the cervical spine. During ultrasound guided procedures, the operator may be forced into an awkward position of the trunk, neck, and upper extremities while maintaining a firm grip on the ultrasound transducer. Axial twisting and excessive reach during these procedures can lead to back, neck, and shoulder pain. To avoid these issues, arm abduction should be limited and neutral body positioning maintained by positioning the ultrasound monitor in front of the operator whenever possible.

Treatment of musculoskeletal injuries is multidisciplinary. The most important intervention, rest, may be very difficult to achieve [94]. Eliminating or changing the activity that causes the injury is ideally the first step in treatment. Medication—nonsteroidal anti-inflammatory agents, paracetamol (acetaminophen in the U.S.), muscle relaxants, or oral analgesic agents—is frequently indicated. Therapeutic massage, stretching exercises, physical therapy, yoga and acupuncture may all play a role [86, 87, 94]. If a specific underlying anatomic cause for the pain is identified, steroid injections, blocks, nerve root ablation or surgery may provide benefit.

Injury prevention should be the goal. Designing the interventional facility in accordance with ergonomic principles, as described above, is basic to prevention, as is minimizing or eliminating those practices that predispose to injury. An additional approach is prevention through conditioning [86, 87, 89, 94]. Chang et al. [104] reviewed studies of core strength training for patients with chronic low back pain. They observed that core strength training is more effective than typical resistance training with machines or free weights for alleviating chronic low back pain and recommended focusing on training of the deep trunk muscles. Valenza et al. [105] studied 54 patients with chronic low back pain, randomly assigned to an 8-week Pilates exercise program or to receiving written information only. At the end of the study, the Pilates group had significantly less pain and disability and significantly better flexibility and balance. Yoga has been reported to promote both physical and psychological health, and to treat low back pain [87, 94]. Kumar et al. [106] studied the effect of Isha Hatha yoga in 102 healthy individuals who underwent an intensive 21-day training program, of whom 76 were evaluable. Isha Hatha yoga stresses the physical components of yoga and aims to achieve overall fitness through unique practices and postures. The training resulted in significant improvement in core stability and standing balance. Physical therapy can be used with techniques to foster spinal and extremity movements, limb stretching, and joint mobilization, as well as stabilization exercises with progression to strength, functional, and aerobic training [87]. However, before adopting any conditioning program, consultation with an appropriate therapist is recommended, and any such program should be performed in a stepwise fashion [87].

Radiation Protection Tools

Personal Protective Equipment

For physicians and staff who perform interventional radiology procedures, radiation protection typically requires wearing a protective apron. Although devices exist for providing suitable radiation protection without the need to wear an apron (freestanding, suspended, and mobile shields), they are expensive and often not suitable for every procedure an interventional radiologist needs to perform [107]. Anything that interferes with necessary procedure performance, thereby lengthening the procedure and increasing the dose to the patient and staff, should be avoided [11]. Apron wear contributes to the risk of musculoskeletal injury [108]. Aprons should be chosen carefully and must fit properly [11, 89, 94, 109, 110]. The risk of musculoskeletal injuries due to the apron's weight should also be considered in the optimization of protection [11, 108]. Unless national or local regulations specify a minimum lead or lead equivalent thickness [18], an appropriate thickness should be based on the wearer's under-apron dosimeter readings [11, 15]. The label on the apron is not necessarily a reliable guide to the degree of radiation protection provided [111].

Apron construction is important in determining the distribution of the apron's weight on the shoulders and back. Two-piece aprons (vest and skirt) place less weight on the shoulders than do one-piece aprons worn with a belt; a one-piece apron worn with a belt places less weight on the shoulders than a one-piece apron without a belt [110]. Unfortunately, while some apron designs may be helpful to reduce injury to the upper extremities, none of them reduce the weight supported by the hips.

Aprons do not completely protect the lateral chest wall and axilla due to the presence of arm holes. The addition of a lead-equivalent sleeve significantly reduces radiation dose to this portion of the chest and axilla when compared with standard leaded aprons alone in both clinical and simulated settings [112, 113]. These sleeves may be useful to reduce radiation exposure to the upper outer quadrant of the breast [114, 115].

Leaded eyewear reduces eye radiation exposure substantially. A review of the effectiveness of leaded eyewear showed that the shielding effect ranges from 10% to 90% depending on eyewear design and lead equivalence [116]. In particular, minimizing the gap between the inferior portion of the lens and the wearer's skin is important [117]. The orientation of the wearer's head, complexity of the procedure, and wearer movement also affect the extent of shielding.

Shields

The walls, windows, and doors of fluoroscopy rooms include structural shielding to reduce radiation levels in surrounding areas to acceptable levels. Staff should perform their duties from a shielded control room whenever possible. To avoid interrupting a critical procedure, doors into the fluoroscopic room should not be interlocked. This means that staff should monitor these doors and keep them closed as much as possible.

Fluoroscopes are typically supplied with flexible protective drapes hanging below the table, extensions above the table, and large ceiling-mounted transparent shields. These shields have the potential to provide more protection than PPE alone while not adding weight to the user. Suspended shields are typically 0.5 mm nominal lead-equivalent thickness. The effectiveness of ceiling-suspended shields is closely linked to their proximity to the patient – the closer to the patient, the larger the shadow created by the shield. Ceiling-suspended shields provide protection for the entire head and neck but cannot always be placed to provide effective protection. Even when they are used, protective eyewear should still be worn [118]. All of these shields should be installed and used whenever possible, as proper use can reduce the scatter to the operator by up to 90% [11, 119]. Protection for non-operator staff may be less.

Radioprotective drapes can be placed directly on the patient. These include both sterile single-use and reusable (placed in a sterile bag) versions. Staff must be in their shadow if they are to be effective. Care must be taken with their placement. If they enter the FOV, they will affect tube output and increase patient dose.

Other types of shielding systems are available that are intended to allow some staff to potentially forego traditional PPE. These types of shields typically provide 0.5 – 1.0 mm lead equivalence. Free-standing mobile shields have long been used to protect non-operator staff such as nurses and anesthesia personnel. Careful placement of mobile shields between the patient and staff can create effective radiation shadows, protecting most, if not all, of the body of those in the shadow. There are also shielding systems that resemble traditional PPE and are designed to protect the operator without the added weight of PPE [107, 120, 121]. Some of these are mounted to either the ceiling or a floor-mounted movable gantry [107]. There is some evidence that their use may reduce ergonomic posture risk to the torso compared to conventional lead aprons [122].

There are large, free-standing barrier systems with multiple components that maintain access to the patient while shielding surrounding areas [123-126]. These devices can be heavy and may not be mechanically compatible with fluoroscopic hardware. They can be obtrusive and may limit movement within the fluoroscopy suite. They may limit gantry and table motion and can impede procedural performance if the patient table must be panned during the procedure or steep gantry angles are required. Patient communication and access may also be impeded. Policies are needed to manage these devices in the event of a medical emergency. Barrier systems are also available that are placed on the table-top or gantry [127, 128]. Practical issues include reducing the maximum weight of a patient allowed on the table or unbalancing the fluoroscopic C-arm.

Shield Use

Free standing mobile shields should be rolled into an appropriate position when needed to supplement table-mounted shielding. For example, they should be used to protect staff when they are working near the patient's head, feet, or other areas outside of the shadows of other radiation protective devices. Versions are available that are intended to provide an additional layer of operator protection where necessary.

Large free-standing barrier systems can be moved into place at the start of a procedure. It is not practical to move them routinely during the procedure. Adequate attention must be paid to minimizing gaps in their radiation shadow throughout the procedure. These barrier systems may provide a radiation shadow sufficient to allow operators to work without PPE. While they can remove the need for personal PPE for the operator for some procedures, they generally only protect a limited number of staff on the operator's side [126]. Others in the room still require PPE.

Depending on local badging requirements, occupational monitoring may need to be modified to account for the use of protective devices that allow staff to perform procedures without wearing PPE. Occupational dosimetry data can be useful to study the effectiveness of the radiation protection strategies in use and to further optimize them.

Practical Advice to Reduce or Minimize Occupational Dose

In both fluoroscopy and CT fluoroscopy, decreasing patient dose will result in a proportional decrease in scatter dose to the operator [11]. Therefore, techniques that reduce patient dose will generally also reduce occupational dose. This is a "win-win" situation: operators, staff, and the patient all benefit. For any intervention, review existing imaging studies to define the relevant anatomy and pathology and to plan the interventional procedure. Good procedure planning prior to the intervention will help reduce procedure time and radiation dose.

Operators and all staff involved in the procedure should have a general knowledge of safe operating practices in a radiation environment. Operators should be thoroughly familiar with the operation of each fluoroscope and CT scanner that they use. If appropriate medical simulators are available, operators and trainees should consider using them to learn and practice new skills before applying them to patients.

All interventional radiology operators and staff need to know their own occupational dose to ensure that they are working safely. The only way to know this is to wear one's dosimeter(s). Occupational dose information will not be accurate unless dosimeters are always worn and worn correctly.

Fluoroscopically Guided Procedures

Specific techniques can be used with fluoroscopically guided procedures to reduce occupational dose. The recommendations given here are largely unchanged from those in the previous version of this guideline [129].

Minimize fluoroscopy time. Fluoroscopy should be used only to observe objects or structures in motion. Review the last-image-hold image or fluoroscopy loop for study, consultation or education instead of using additional fluoroscopic exposure. If available, record a fluoroscopy loop to review dynamic processes. Use short taps of fluoroscopy instead of continuous operation. Fluoroscopy to determine or adjust collimator blade positioning can be eliminated by using the virtual collimation feature, when present, in conjunction with a last-image-hold or fluoroscopy loop image.

Minimize the number of radiographic images. For digital subtraction angiography, use variable frame rates tailored to the examination (e.g., 1 image/sec for 6 seconds, then 1 image every other second for 24 seconds for arteriography of the celiac axis) instead of a constant frame rate (e.g., 2 images/second for 30 seconds). Tables of suggested imaging sequences were available in some older standard interventional radiology textbooks but are absent in most current textbooks. For documentation, use stored last-image-hold images instead of acquiring radiographic images if the last-image-hold images provide acceptable image quality. When available, use a stored fluoroscopy loop instead of a radiographic acquisition (digital subtraction angiography) if the image quality is adequate to document the findings.

Use the lowest dose settings that provide adequate image quality together with all available patient dose reduction technologies. These include low fluoroscopy dose-rate settings, low frame-rate pulsed fluoroscopy, removal of the anti-scatter grid for infants, small children, and

small body parts in adults [130-132], spectral beam filtration, and use of increased x-ray beam energy. Catheters with highly radiopaque tips are easier to see. Improved image processing within the fluoroscopic unit can compensate to a considerable degree for the reduced image quality due to decreased exposure levels. This technique reduces dose at the cost of somewhat decreased image quality.

Use good imaging-chain geometry. Position the patient table at a comfortable height for the operator unless patient peak skin dose is a concern, in which case the distance from the patient to the X-ray tube should be maximized. Place the image receptor as close as possible to the patient.

Collimate. Adjust collimator blades tightly to the area of interest. Tight collimation reduces patient dose and improves image quality by reducing scatter. When beginning a case, position the C-arm over the area of interest, with the collimators almost closed. Open the collimators gradually until the desired FOV is obtained. When possible, position the collimator blades without fluoroscopy by using virtual collimation.

Operators and staff should position themselves in a low scatter area and stay as far away from the x-ray beam as possible. Operators should use tubing extensions or needle holders so that their hands are away from the exposed field. Operators should never place their hands in the x-ray beam. Use power injectors for contrast material injections when feasible and step out of the procedure room during radiographic acquisitions (digital subtraction angiography and cone-beam CT). When using angled or lateral projections, remember that the highest intensity of scattered radiation is located on the x-ray beam entrance side of the patient. When using these projections, the x-ray tube should be on the side opposite the operator whenever possible. Avoid using equipment with over-the-table x-ray tubes for interventional procedures.

Use protective shielding. A personal protective apron, a thyroid shield, and protective eyewear should be worn when performing fluoroscopically guided interventions. Ceiling-suspended shields can provide significant additional dose reduction, especially to unprotected

areas of the head and neck. Leaded eyewear is recommended even if ceiling-suspended shields can be used continuously during the entire procedure. Under-table lead drapes reduce lower extremity dose substantially and should be used whenever possible.

Use appropriate fluoroscopic imaging equipment. Imaging systems optimized for one type of procedure or body part may be suboptimal for others. Using fluoroscopy equipment under suboptimal conditions frequently results in increased radiation dose. Furthermore, high radiation dose procedures should be performed with fluoroscopic systems that incorporate recommended dose-reduction technology and comply with the most current International Electrotechnical Commission (IEC) standard [133]. Encourage your institution to purchase this kind of equipment for interventional laboratories.

Use guidance tools when available. Biopsy planning and navigation systems, marking vascular origins with fluoroscopy overlays during stent placement, and vessel tracking to identify the course of small vessels can all be valuable guidance tools for interventional procedures.

Radioembolization

Details of the radioembolization pre-procedure, procedure, and post-procedure processes are provided elsewhere [134, 135]. In addition to occupational exposure from the fluoroscopic component of the procedure, interventional radiologists and other staff are exposed during transcatheter delivery of radioactive microspheres into the hepatic artery. Nurses are exposed during and after the procedure until patient discharge, though exposure from the radiopharmaceutical itself is very low after the procedure and well below any regulatory thresholds.

Procedures and safety measures are required to protect operators and other healthcare workers from occupational radiation exposure during radioembolization procedures. The facilities and procedures required depend in part on national regulations. In Europe and the U.S., specific licenses are required for handling and administrating radioactive material [134, 136]. The facility where treatment is administered must have appropriate personnel and radiation safety equipment, as well as procedures for waste handling

and disposal, and the monitoring, controlling, and handling of potential contamination [135]. The instructions provided by the manufacturer should be followed. Reported equivalent doses (Hp(10)) are less than 2 μSv/GBq for both glass and resin 90Y microspheres for preparation and injection [11].

After radioembolization is completed, all exposed and possibly exposed medical products are placed into a separate decontamination container. All personnel in the fluoroscopy room are tested for contamination before leaving. The room is measured for any residual contamination before being cleared by radiation safety personnel before the next procedure [134]. In some countries this is a regulatory requirement.

Recommendations to minimize finger and hand exposure are included in the guideline [1]. Reported finger exposure for the operator injecting the microspheres is 14.0 ± 7.9 μSv/GBq with ^{90}Y glass microspheres and 235.5 ± 156 μSv/GBq for ^{90}Y resin microspheres [137]. With ^{166}Ho, reported whole-body doses were less than 3 μSv/GBq and maximum finger dose for the operator was $2.5 \pm 0.3 \times 10^3$ μSv/GBq (2.5 ± 0.3 μSv/MBq) [138].

A finger (ring) dosimeter should be worn on the index finger of the hand closer to the radiation source. Ring dosimeter doses from radioembolization may be severely underestimated due to their limited sensitivity to beta emissions, the small distances between the beta source and the skin, and the high dose gradients involved [139]. To account for this, measured dose rates can be complemented by an assessment of theoretical dose rates using phantoms and dedicated software [135, 140].

Immediately after hepatic radioembolization with ^{90}Y microspheres, the radiation field at 1 m from the patient's abdomen is 1.14 μSv/h/GBq [141]. This gives 3 μSv/h for typical 2.6 GBq glass microsphere administration, and 1.8 μSv/h for 1.6 GBq resin microspheres. Another study determined mean equivalent dose rates of 1.1 mSv/h at 1 m for ^{90}Y resin spheres and 2.4 mSv/h at 1 m for ^{90}Y glass spheres [142]. For ^{166}Ho, external exposure at 1m ranges from 8 to 60 μSv/h [143].

CT-guided Interventions

From an occupational protection point of view, intermittent CT is preferable to CT fluoroscopy [144]. By stepping into the control area during longer spiral scans (e.g., pre-procedural planning scan and post-procedure scan) the operator and staff take advantage of structural shielding in the walls and windows of the procedure room. This limits the time during which they are directly exposed to scatter radiation. An important note here is that an open doorway provides no additional protection – the operator and staff should take care to ensure they do not have a direct unprotected line of sight to the patient while X-rays are emitted [145].

Infection control requirements may influence the choice of radiation protection strategies, particularly if transit between the procedure room and control room is not possible. Individuals who must remain in the room during scanning should position themselves as far from the CT bore as possible while the X-ray source is energized, preferably off to the side of the gantry rather than at the head or foot of the patient. The gantry provides protection from radiation because the primary x-ray beam is attenuated by the CT detectors and the bulk of the gantry [144, 145]. Rolling shields can also be used to supplement protection. They are effective for protecting individuals who may need to remain in the room.

A lead drape or single-use sterile protective drape can be useful when performing CT fluoroscopy guided procedures [146]. A lead drape placed over the patient absorbs scattered radiation from the patient and decreases operator exposure to radiation by up to 96% [144]. However, the protection provided by such drapes depends strongly on their proximity to the area where the primary beam strikes the patient, which in CT is often very narrow. Protective drapes should be placed on the patient only after the pre-procedural planning scan has been acquired. If tube current modulation is used, the presence of a drape in the pre-procedural planning scan can drastically increase the radiation dose to both patient and operator.

When CT fluoroscopy is used to guide the procedure, the operator's hands should never be in the CT scan plane during scanning; needle holders should always be used [144, 147]. Operators should always wear a lead apron, thyroid shield, and leaded glasses [144, 148]. A table-mounted lower body shield is useful [149]. Use of a ring dosimeter will provide the operator with information on hand exposure. Staying as far as possible from the scan plane will minimize operator dose, especially to the

operator's hands, eyes and thyroid [146]. In one study using an anthropomorphic hand voxel phantom, the dose to the operator's hand in the CT scan plane was 18.1 mGy/sec [150]. When procedures are performed with CT fluoroscopy, long needle holders and other instruments should be used despite the potential drawbacks of these instruments, which include reduced sensitivity and tactile feedback [145]. Suspended shields are generally not useful in CT-guided interventions, and radioprotective gloves offer limited protection at the beam quality (i.e., energy) used in CT [145]. The nominal transmission through PPE is higher for CT scatter as compared to transmission from FGI procedures due to the higher operating kVp of CT radiation beams.

For most CT guided procedures, CT fluoroscopy is not necessary [144]; intermittent CT ("quick-check" or "step and shoot") is adequate. Use of this technique substantially decreases CT times and radiation dose and avoids direct exposure of the operator's hand [144, 147].

Adjusting CT fluoroscopy scan parameters (voltage, tube current, slice thickness) can reduce operator dose substantially [146]. Ekpo et al. [151] demonstrated a 26% increase in radiation dose to the operator's eyes with an increase in tube voltage from 120 kV to 135 kV, and a 2-fold increase in radiation dose when the tube current was doubled from 10 mA to 20 mA. However, excessive reduction in scan parameters may result in CT images that are inadequate clinically.

If the CT scanner can reconstruct images obtained with less than a 360-degree irradiation (partial angle scanning), this should be used. When used properly, it can result in reduced operator radiation dose [152]. The lowest operator dose during partial angle CT is achieved when the operator stands on the detector side (i.e., distant from the tube) and in one study was 35% less than when 360-degree scanning was performed [152]. However, the single most effective method to reduce operator and patient dose is to minimize CT beam-on time [11, 144].

While CT fluoroscopy has a much higher dose rate than fluoroscopy with a C-arm, CT-guided procedures tend to require much less beam-on time. As a result, operator doses tend to be lower than for a typical FGI procedure. Jiang et al. estimate that, on average, an interventional radiologist would need to

perform nine CT fluoroscopy procedures to receive the same occupational radiation dose received from a single C-arm fluoroscopy procedure [153].

It is sometimes necessary to perform tumor biopsy or ablation with PET-CT guidance because the lesion is not seen adequately on other modalities, or the goal is to target metabolically active portions of tumors, or there is a need to assess ablation margins during the procedure [154-156]. However, PET-CT procedures expose the operator and staff to radiation from both CT and the PET radiopharmaceutical. Options to reduce operator exposure from PET radiopharmaceuticals are limited because of the high energy (511 keV) positron-electron annihilation photons that are produced. Lead or lead-equivalent aprons are ineffective as they attenuate less than 8% of PET radiation [11, 157]. Mobile shields that provide adequate protection and do not interfere with procedures are not commercially available. Some methods that can be used include using lower or split radiopharmaceutical doses, avoiding standing next to the patient for long time, and dividing the procedure among multiple operators [156].

Fortunately, PET radiation contributes only a small fraction to patient radiation doses and personnel exposure during PET-CT-guided procedures [11, 155]. In 21 PET-CT-guided ablations, Jiang et al. found no detectable radiation due to PET behind the operator's thyroid shield [157]. Similarly, the nurses and anesthesiologist had no detectable radiation exposure from the 21 procedures. This was likely due to their limited time near the patients. However, even in the worst-case scenario of prolonged proximity to the patients, their PET radiation dose would still be only 0.02 mSv per procedure [157]. Jiang et al. also tested using a rolling shield with 25 mm lead equivalence to protect the operator in addition to the operator's standard lead apron. They determined that the shield provided only limited benefit because of the low exposure levels due to PET.

As of 2025, PET-CT fluoroscopy with fusion of the CT images with previously obtained PET images is not generally available but likely will be in the future [158]. PET-CT fluoroscopy allows rapid acquisition and display of CT fluoroscopy images fused to intraprocedural PET images during intermittent CT fluoroscopy. It has the potential to decrease operator time near the patient, a prime

determinant of occupational dose from PET radiopharmaceuticals [11]. However, its value for guidance, radiation dose reduction, and improvement in procedure success have not yet been evaluated in detail.

Training

Individuals who participate in interventional radiology procedures need appropriate initial and periodic training [133, 159]. These individuals can be divided into two groups. One group includes those whose clinical responsibilities include patient radiation dose management before, during, or after procedures; the second includes all other staff in the room during a procedure. These groups are professionally diverse, including physicians, radiographers, nurses, surgical assistants, and others. Training should be based on their responsibilities in the procedure room [133, 160]. **Table 4** provides a summary. All physicians who perform interventional procedures are in group A. Other operators (in the U.S., nurse practitioners for example) may be in Group B. Training for those whose practice includes pediatric procedures needs to include additional considerations for this population. Training is recommended for non-operators (e.g., nurses, physician assistants) whose duties include assisting with patient radiation management before, during, or after procedures (Group D) [133]. Training topics for interventional radiologists and staff are described in detail in ICRP and NCRP publications [11, 133, 159]. The International Atomic Energy Agency provides a free training program that can be downloaded at https://www.iaea.org/resources/rpop/resources/training-material#8. A great deal of other information is available on the internet. The internet is a source of both useful information and potentially bad misinformation. Readers should view web-based resources with caution.

Initial and periodic refresher training are both needed. Lifetime certification is inappropriate because of continuing changes in technology and clinical practice. The ideal initial radiation protection curriculum is individualized and based on the students' backgrounds and duties [159, 161]. Periodic

refresher training should be a subset of the individual's initial training. An overview of the initial training content recommended for interventional radiologists (Group A) is provided in ICRP, NCRP and European Commission documents [133, 159, 162]. Subsets of this material are appropriate for refresher training of interventionalists and for the training of Groups B-E.

Non-physician instructors, typically medical physics experts, need sufficient experience with clinical procedures to be able to provide practical advice. Facility managers need to provide multiple forms of support to this process. Managers should have sufficient training so that they understand the range of patient and staff hazards associated with FGI training topics for interventional radiologists.

Modern interventional fluoroscopy systems are extremely complex and highly sophisticated. They provide many different fluoroscopic imaging and radiographic acquisition modes (e.g., low, medium and high dose fluoroscopy, high level control mode fluoroscopy, digital cineradiography, digital subtraction angiography, cone beam computed tomography) with multiple choices of pulse rate and frame rate and different options for image postprocessing. Interventional radiologists should know, for each mode, the relative differences in patient and staff radiation doses and image quality or diagnostic information. These may vary from fluoroscope to fluoroscope, even among fluoroscopes from the same manufacturer, depending on how they were set up during installation and subsequently configured. The effect of collimation, C-arm angulation, source-to-image-receptor and source-to-skin distances, and magnification on patient and staff doses is an essential part of these training programs. The medical physics expert is best able to provide this information. Fluoroscopes from different manufacturers also differ greatly in the location, operation, and function of tableside controls. Each operator of a fluoroscope needs to be familiar with the tableside controls of every fluoroscope they use [133].

All individuals who work in an interventional radiology facility need to know and be familiar with the available radiation protection tools (e.g., protective garments, ceiling-suspended screens), the level of protection they provide, and how best to use them. This includes an understanding of the purpose, value, and proper use of personal dosimeters, whether passive or active, and the C-arm ambient dosimeter, if one is used [11].

The absence of practical, hands-on training in radiation protection is a major problem identified by health professionals involved in the medical use of ionizing radiation [163]. Virtual reality has been identified as an effective radiation safety learning tool [164]. It provides a visual and active learning experience [165, 166]. One example that has worked well with students is the set of virtual labs provided on the IAEA website (https://www.iaea.org/resources/rpop/resources/online-training-in-radiation-protection). The German Federal Office for Radiation Protection sponsored the development of an application that simulates a virtual interventional fluoroscopy room (https://www.bfs.de/SharedDocs/Pressemitteilungen/BfS/EN/2024/007.html). The software is free and available at https://app.meditrainvr.com/. Scattered radiation and the shielding effect of patient protection products can be visualized in the software, and the entire set-up of an interventional fluoroscopy system can be explored systematically. Commercial products that simulate interventional procedures for both training and specific case preparation have been developed and are becoming popular for training. These simulators include tools to demonstrate the influence of different parameters on the radiation dose.

Glossary

Absorbed dose: the energy imparted to matter by ionizing radiation per unit mass of irradiated material at the point of interest. In the Système Internationale (SI), the unit is J kg^{-1} with the special name gray (Gy) [15].

Accreditation: with respect to radiation protection training, accreditation means that a training supplier has been approved by an appropriate body to provide education or training [159].

Cohort study: a research study that compares a particular outcome (such as lung cancer) in groups of individuals who are alike in many ways but differ by a certain characteristic, such as occupational radiation exposure. In a cohort study setting, random errors in estimates of dose tend to drive an association toward null (no effect) rather than to artificially inflate, or induce, an association.

Detriment: the total harm to health experienced by an exposed group and its descendants because of the group's exposure to a radiation source. Detriment is a multi-dimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable non-fatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs [3].

Dose equivalent: a measure of the biological damage to living tissue as a result of radiation exposure. Also known as the "biological dose", the dose equivalent is calculated as the product of absorbed dose in tissue multiplied by a quality factor and then sometimes multiplied by other necessary modifying factors at the location of interest. The dose equivalent is expressed numerically in rems or sieverts (Sv) [167].

Dose limit: the value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded [3]. The intent is to prevent the occurrence of radiation-induced tissue reactions or to limit the probability of radiation-related stochastic effects.

Equivalent dose: the dose in a tissue or organ T given by:

$$H_{\mathrm{T}} = \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}}$$

where $D_{\mathrm{T,R}}$ is the mean absorbed dose from radiation R in a tissue or organ T, and w_{R} is the radiation weighting factor. Since w_{R} is dimensionless, the unit for the equivalent dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv).

Effective dose: the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$E = \sum_T w_T \sum_R w_R D_{T,R}$ or $E = \sum_T w_T H_T$

where H_T or $w_R D_{T,R}$ is the equivalent dose in a tissue or organ, T, and w_T is the tissue weighting factor. the unit for effective dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv) [3]. Effective dose (E) applies only to stochastic effects.

Effective dose equivalent: the sum of the products of the dose equivalent to the organ or tissue (H_T) and the weighting factors (w_T) applicable to each of the body organs or tissues that are irradiated ($H_E = \Sigma w_T H_T$) [167].

Equivalent dose: (H_T): mean absorbed dose in a tissue or organ ($D_{T,R}$) weighted by the radiation weighting factor (w_R) for the type and energy of radiation incident on the body:

$H_T = \sum_R w_R D_{T,R}$

The unit of organ equivalent dose is J kg^{-1} and has the special name sievert (Sv).

Excess relative risk: the rate of disease in an exposed population divided by the rate of disease in an unexposed population, minus 1.0. This is often expressed as the excess relative risk per Gy or per Sv [3]. (See also relative risk.)

Fluoroscopically-guided interventional procedure: an interventional diagnostic or therapeutic procedure performed via percutaneous or other access routes, usually with local anesthesia or intravenous sedation, which uses external ionizing radiation in the form of fluoroscopy to: localize or characterize a lesion, diagnostic site, or treatment site; monitor the procedure; and control and document therapy [15].

Gray: the special name for the SI unit of absorbed dose: 1 Gy = 1 J kg^{-1} [3].

K-edge: the binding energy of the innermost electron shell (K-shell) of an atom. There is a marked increase in x-ray absorption of X-rays whose energy is just above the K-edge due to the photoelectric effect.

Interventional Radiology: the medical specialty that uses image guided techniques to diagnose, treat, follow up and palliate a broad range of pathologies [168].

Maximum permissible dose: in the U.S., a regulatory dose limit.

Occupational radiation exposure: radiation exposures to individuals that are incurred in the workplace because of situations that can reasonably be regarded as being the responsibility of management (radiation exposures associated with medical diagnosis of or treatment for the individual are excluded) [15].

Odds ratio: the ratio of the odds of an event occurring in the exposed group to the odds of the event occurring in the non-exposed group. It is commonly used in case-control studies, where the incidence rates of the outcome are not directly measured, but given the outcome the odds of exposure can be calculated.

Operational quantities: quantities used in practical applications for monitoring and investigating situations involving external exposure. They are defined for measurements and assessment of doses in the body [3].

Personal Protective Equipment: garments and devices worn to protect against radiation exposures, such as aprons, thyroid shields and leaded eyewear.

Posture: the spatial arrangements of body parts as they align to perform a task

Rad: a unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/gram or 0.01 joule/kilogram (0.01 gray) [169]. For x-rays and gamma rays, 1 rad = 1 rem = 10 mSv.

Relative risk: the ratio of the probability of an event occurring in the exposed group to the probability of the event occurring in the non-exposed group. It is typically used in cohort studies and randomized controlled trials, where the incidence of an outcome can be measured directly.

rem (Roentgen equivalent man): a special unit of any of the quantities expressed as dose equivalent. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor (1 rem = 0.01 sievert) [169]. The quality factor for x-rays is 1.

Sievert: The special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram (J kg^{-1}).

Stochastic effect: malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold [3].

Tissue reaction: Injury in populations of cells, characterized by a threshold dose and an increase in the severity of the reaction as the dose is increased further. Also termed tissue reaction. In some cases, tissue

reactions are modifiable by post-irradiation procedures including biological response modifiers [3]. These were previously called ‘deterministic effects’.

Tissue weighting factor: the dimensionless factor by which equivalent dose is weighted to represent the relative contribution of that tissue or organ to the total radiation detriment resulting from uniform irradiation of the body. The w_Ts are judgment values grouped by organs and tissues in the interest of simplicity and rounded to sum to 1.0 [170].

Training: applied knowledge and practical aspects of a topic that result in improved efficiency and productivity [159]**.**

Uncertainty: lack of sureness or confidence in predictions of models or results of measurements [170].

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TABLES

Table 1. Cancer incidence and mortality in the U.S. population, by year, calculated using data from the Surveillance Epidemiology and End Results (SEER) Program [50]

Years	**Probability of developing cancer (%)**
2018-2021 (2020 excluded) [a]	39.33
2015-2017	40.85
2012-2014	40.91
2009-2011	42.81
	Probability of dying of cancer (%)
2018-2021 (2020 excluded)	17.89
2015-2017	19.53
2012-2014	20.36
2009-2011	20.87

[a] 2020 data excluded because of the effect of COVID-19

Table 2. Results from selected large worker cohorts that examined cancer risks associated with occupational radiation exposure. Statistically significant results are shown in bold.

First author, publication year	Cohort	Outcome (N)	Measure of effect
Richardson, 2023 [49]	INWORKS (multinational cohort of >300,000 monitored nuclear industry workers)	Deaths due to solid cancer (28,089) Deaths due to lung cancer (19,950)	**ERR/100 mGy: 0.05 (90% CI: 0.03, 0.08)** **ERR/100 mGy: 0.04 (90% CI: 0.02, 0.07)**
Leuraud, 2015 [47]	INWORKS (multinational cohort of >300,000 monitored nuclear industry workers)	Deaths due to leukemia, not including chronic lymphocytic leukemia (1,791)	**ERR/100 mGy: 0.30 (90% CI: 0.12, 0.52)**
Preston, 2016 [51]	USRT (cohort of >110,000 U.S. radiographers)	Incident breast cancer (1,922) Deaths due to breast cancer (586)	**ERR/100 mGy: 0.07 (95% CI: 0.005, 0.19)** **ERR/100 mGy: 0.31 (95% CI: 0.11, 0.67)**
Velazquez-Kronen, 2020 [52]	USRT (cohort of >110,000 U.S. radiographers)	Deaths due to lung cancer (1,090)	ERR/100 mGy, overall:−0.02 (95% CI: <0-0.13) By smoking intensity: **<20 pack-years: 0.41 (95% CI: 0.01, 1.15**) ≥20 pack-years: −0.03 (95% CI: <0-0.15)
Linet, 2020 [56]	USRT (cohort of >110,000 U.S. radiographers)	Deaths due to leukemia, not including chronic lymphocytic leukemia (155)	ERR/100 mGy: 0.05 (95% CI <-0.09, 0.24)
Kitahara, 2017 [54]	USRT (cohort of >110,000 U.S. radiographers)	Brain cancer mortality (193)	ERR/100 mGy: 0.1 (95% CI < –0.3, 1.5)
Kitahara, 2018 [55]	USRT (cohort of >110,000 U.S. radiographers)	Incident thyroid cancer (476)	ERR/100 mGy: -0.05 (95% CI <–0.10, 0.34)

Lee, 2015 [53]	USRT (cohort of >110,000 U.S. radiographers)	Incident basal cell carcinoma (3,615)	ERR/100 mGy: -0.001 (95% CI: -0.004, 0.005)
Linet, 2017 [60]	45634 "exposed" U.S. physicians (>90% males) who performed interventional radiology procedures (37311 cardiologists, 5520 interventional radiologists, and 2803 neuroradiologists) and 64,401 "unexposed" U.S. psychiatrists	Deaths due to cancer (1140 in exposed males; 2154 in unexposed males)	Exposed vs. unexposed, RR (males): 0.92 (95% CI: 0.85, 0.99) [a]
Simpson, 2024 [61]	1265 cancer cases and 5772 controls.		OR per 1000 ionizing radiation procedures: 1.02 (95% CI: 0.99, 1.05)

ERR excess relative risk; *RR* relative risk; *OR* Odds ratio; *CI* Confidence interval; *USRT* U.S. Radiologic Technologists Study

ERR per unit dose is approximately equal to the RR per unit dose minus 1.

[a] No significantly increased risks observed for specific causes of cancer death

Table 3. Results from selected large worker cohorts examining tissue reactions associated with occupational radiation exposure. Statistically significant results are shown in bold.

First author, publication year	Cohort	Outcome (N)	Measure of effect
Little, 2018 [74]	USRT (cohort of >110,000 U.S. radiographers)	Incident cataract (12,336) Surgically-removed cataracts (5,509)	**ERR/100 mGy: 0.069 (95% CI: 0.027, 0.116; lagged 5 years)** **ERR/100 mGy: 0.034 (95% CI -0.019, 0.097; lagged 5 years)**
Velazquez-Kronen, 2019 [65]	USRT (cohort of >110,000 U.S. radiographers)	Incident cataract (9,372)	**Ever vs never worked with interventional radiology procedures, RR: 1.18 (95% CI 1.11 to 1.25)** **Higher risk with greater procedure frequency, particularly when standing <3 feet of the patient**
Little, 2018 [76]	USRT (cohort of >110,000 U.S. radiographers)	Incident glaucoma (1,631) Incident macular degeneration (1,331)	ERR/100 mGy: -0.06 (95% CI: -0.15, 0.06) ERR/100 mGy: 0.03 (95% CI: -0.03, 0.13)
Gillies, 2017 [78]	INWORKS (multinational cohort of >300,000 monitored nuclear industry workers)	Deaths due to circulatory disease (25,570) Deaths due to respiratory disease (5,291) Deaths due to digestive disease (2,180) Deaths due to external	**ERR/100 mSv: 0.02 (90% CI: 0.01, 0.04)** [a] ERR/100 mSv: 0.01 (90% CI: -0.02, 0.05) ERR/100 mSv: 0.01 (90% CI: -0.04, 0.07) ERR/100 mSv: -0.01

		causes (4,451)	(90% CI: -0.06, 0.05)
Bang et al., 2023 [79]	Cohort of >50,000 Korean male diagnostic medical radiation workers	Deaths due to circulatory disease (320)	ERR/100 mGy: 0.85 (95% CI: -0.11, 1.82) [b]
Linet, 2017 [60]	45634 "exposed" U.S. physicians (>90% male) who performed interventional radiology procedures (including 37311 cardiologists, 5520 interventional radiologists, and 2803 neuroradiologists) and 64,401 "unexposed" U.S. psychiatrists	Deaths due to cardiovascular diseases (1299 in exposed males; 2642 in unexposed males) Deaths due to neurological and mental conditions (149 in exposed males/280 in unexposed males)	Exposed vs unexposed, RR (males): 0.87 (95% CI: 0.82, 0.93) [c] Exposed vs unexposed, RR (males): 0.94 (95% CI: 0.77, 1.15)
Dauer, 2024 [80]	517,608 workers from 6 cohorts within the Million Person Study	Deaths due to Parkinson's disease	ERR/100 mGy: 0.17 (95% CI: 0.05, 0.29)
Azizova, 2020 [81]	22,377 Russian nuclear production facility workers	Incident Parkinson's disease (300)	ERR/100 mGy: 0.10 (95% CI: 0.06, 0.16)
Laurent, 2022 [82]	80,348 French nuclear workers	Deaths due to Parkinson's disease (124) Deaths due to dementia/Alzheimer's disease (269)	ERR/100 mGy: -0.13 (95% CI: n.e., 0.74) ERR/100 mGy: 0.96 (95% CI: 0.31, 1.87)

ERR Excess relative risk*, RR* Relative risk*, n.e.* Not estimable*, CI* Confidence interval

ERR per unit dose is approximately equal to the RR per unit dose minus 1.

[a] Similar results for ischemic heart disease (ERR/100 mSv: 0.02 (90% CI: 0.00, 0.04)) and cerebrovascular disease (ERR/100 mSv: 0.05 (90% CI: 0.01, 0.09))

[b] Similar results for ischemic heart disease (ERR/100 mGy: 1.18, 95% CI -0.69, 3.05) and cerebrovascular disease (ERR/100 mGy: 0.23, 95% CI -0.48, 0.94)

[c] No increased risks for specific types of cardiovascular disease deaths

Table 4. Training groups (modified with permission from [133])

Group	Individuals in the Group	Staff Risk for	Patient Risk per procedure of	
		Stochastic Injury	Stochastic Injury	Tissue Reaction
A	Operators[a] performing potentially high patient dose procedures	Minimal to minor	Low	Possible
B	Operators[a] performing intermediate patient dose procedures	Minimal to minor	Minimal to minor	Highly Unlikely
C	Operators[a] performing only low patient dose procedures	Minimal	Negligible	Not Expected
D	Other individuals[a] assisting with patient radiation management[b]	Minimal	N/A	N/A
E	All other individuals in the fluoroscopic room while procedures are in progress[b]	Minimal	N/A	N/A
F	All other individuals in the facility who might encounter a fluoroscope or enter a fluoroscopic room	Simple instruction, integrated into the facility's general safety training		

Modified from "NCRP Commentary No.33. Recommendations for stratification of equipment use and radiation safety training for fluroscopy". Copyright 2021, used with permission from the National Council on Radiation Protection and Measurements.

[a] This also includes those who supervise these individuals

[b] Content should be adjusted to meet the individual's professional background and the needs of the highest risk procedures that they support

FIGURES

Fig.1. The reference (or ambient) dosimeter is located on the C- arm to measure the level of scatter radiation produced in the interventional rooms. This reference dosimeter is attached to the lower part of the C- arm (**arrow**). Well-protected operators should receive much lower doses than these reference

dosimeters. Reproduced with permission from [12]. Reproduced with slight modification from Medical Physics, Vol. 48(10), Sánchez RM, Fernández D, Vañó E, Fernández JM., "Managing occupational doses with smartphones in interventional radiology", Pages 5830-5836, Copyright 2021. Reproduced with permission from John Wiley and Sons, used under the Creative Commons Attribution Non-Commercial-NoDerivatives 4.0 International deed (CC-BY-NC-ND 4.0)

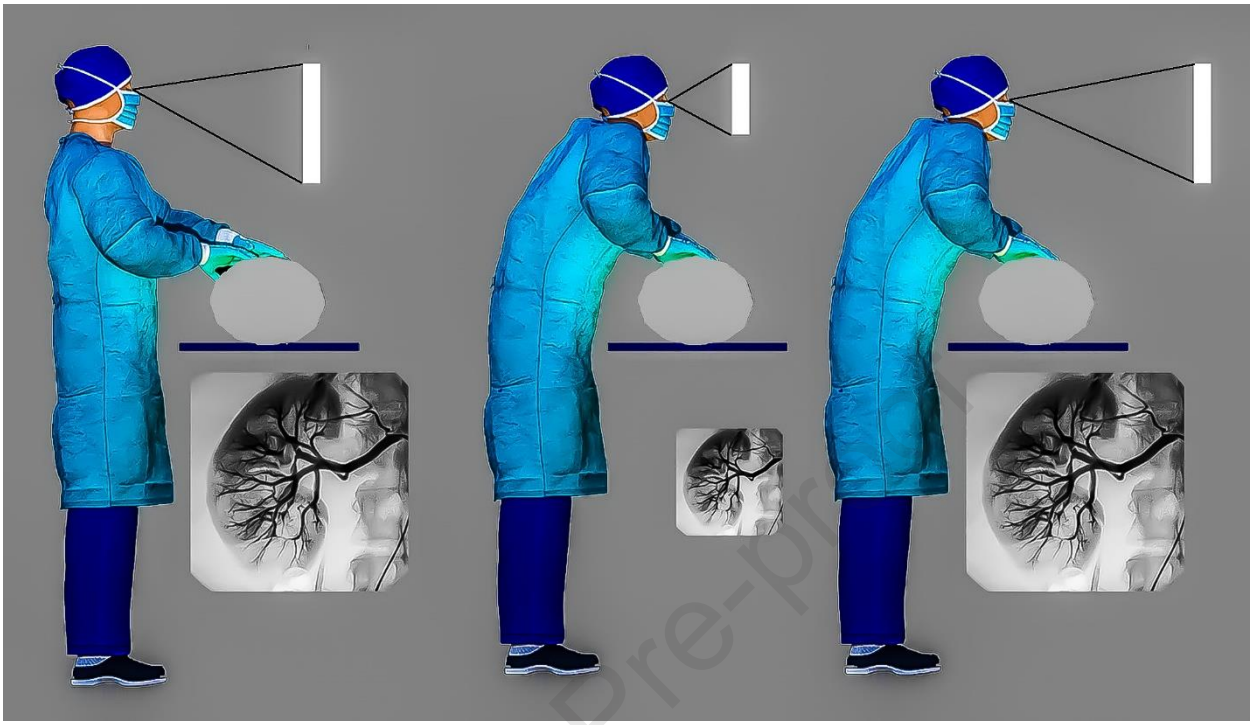

Fig.2. **Left.** With the monitor positioned appropriately (vertical white rectangle), the operator can see detail in the fluoroscopic image while maintaining a neutral spine position. Note also that table height is appropriate, so that proper arm and elbow position are achieved. **Center.** With a smaller monitor or smaller image, the monitor must be moved closer to the operator for details in the displayed image to be appreciated. If this is not done, operators are more likely to lean over the patient to improve their ability to see image detail. **Right.** Even with a large monitor and a large image, if the monitor is placed too far from the operator, proper posture is not maintained.