3

Radiation Safety

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Introduction

Increasing numbers of medical specialists are performing fluoroscopy-guided interventional procedures (FGIP) [1, 2]. The use of medical ionizing radiation in the USA was reported sevenfold higher in 2006 compared to 1980, when the amount due to FGIP increased 33 times [3, 4]. The new international recommendations on radiation safety have led to national and international efforts to promote patient and staff radiation safety.

Inherent in the growing use of medical radiation is a better understanding of the potential stochastic risks for cancer and the methods to monitor and reduce the risk of deterministic effects for skin injury. Modern angiography systems allow virtually unlimited exposure. CT or MR angiography are routinely used for most endovascular procedures. It is generally believed that the exposure to the staff is not significant and does not represent a real hazard. In fact, there is real risk to operators and staff of both tumor formation and damage to the eyes. Planning of each and every intervention should comprise radiation protection measures as part of the procedure [5]. Lack of radiation protection training of those working with fluoroscopy can increase the radiation risk to workers and patients alike. Patient dose monitoring is essential whenever fluoroscopy is used. The International Commission on Radiological Protection (ICRP) recommended that manufacturers should develop systems to indicate patient dose indices with the possibility of producing patient dose reports and shielding screens that can be effectively used for the protection of workers using fluoroscopy without hindering the clinical task [6].

Obesity is recognized worldwide as an epidemic causing devastating or fatal health disorders, such as diabetes and heart disease [7, 8]. The scatter radiation exposure to the operator's waist increases dramatically with obese patients. It doubles with each additional 5 cm (1.97 in) of patient thickness; patient entrance air kerma increases by a factor of 8.4 when thickness increased from 24 to 34 cm [9–15]. Complex FGIP are associated with high radiation doses. These procedures can result in patient skin doses that are high enough to cause radiation injury and an increased risk of cancer [16].

Key Points

Specialties that utilize image guidance:
Interventional radiology
Diagnostic radiology
Urology
Gastroenterology
Orthopedic surgery
Vascular surgery
Trauma and general surgery
Anesthesiology
Cardiology

Pediatric patients have a higher average risk of developing cancer compared with adults receiving the same radiation dose. The longer life expectancy in children allows more time for any harmful effects of radiation to manifest, and developing organs and tissues are more sensitive to the effects of radiation. Special attention is required to optimize appropriate protocols for pediatric patients. Major pediatric interventional procedures should be performed by experienced pediatric interventional operators, preferably with additional training in radiological protection [17, 18].

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The Society of Interventional Radiology (SIR) and the Cardiovascular and Interventional Radiology Society of Europe (CIRSE) have jointly produced several guidelines that should be part of the education material for trainees aiming to be interventionists:

1. Patient Radiation Dose Management [19]
2. Occupational Radiation Protection in Interventional Radiology [20]
3. Radiation Management for Interventions using Fluoroscopic or Computed Tomographic Guidance during Pregnancy [21]
4. Occupational Radiation Protection of Pregnant or Potentially Pregnant Workers in Interventional Radiology [22]

X-ray Systems for Interventional Radiology

X-ray and imaging systems for interventional radiology are complex and have several modes to acquire images using different levels of radiation dose depending on the required image quality and diagnostic information for the clinical task. New technology in interventional imaging systems allows for substantial reduction in patient doses while maintaining enough image quality and diagnostic information, thanks to advanced image processing and refined selection of technical parameters during the imaging acquisition. During the commissioning of x-ray systems, some basic information about the modes of operation should be obtained [23].

Basic Radiation Physics Units

- *Absorbed dose* is the energy absorbed per unit mass. The unit of absorbed dose is the gray (Gy); 1 gray is 1 Joule per kilogram.
- *Air kerma* is the kinetic energy released in a mass of air. For the x-ray energies utilized in interventional procedures, the air kerma is numerically equal to the absorbed dose in air. The units for air kerma are the gray (Gy) or milligray (mGy) (Fig. 3.1).
- *The dose-area product (DAP)* also called the kerma-area product (KAP) is the sum of the products of the incident doses and the areas of the x-ray fields for all segments of an interventional procedure. It can be determined at any convenient location between the x-ray source and the patient. The practical used unit for DAP is Gy·cm^2. This quantity is presented by most of the interventional x-ray systems during the procedures, and the cumulative value is reported at the end of the procedure (Fig. 3.1).
- *Air kerma at the patient entrance reference point*. This "patient entrance reference point" is located 15 cm from the isocenter in the direction of the focal spot for C-arm interventional x-ray equipment (Fig. 3.2). These two quantities (DAP and air kerma) are the most used by the x-ray systems to show interventionists the radiation dose received by the patients [24].
- *Equivalent dose* is derived from the absorbed doses in specific tissues, weighted by the relative effect of the type and energy of the radiation encountered. For x-rays used in interventional procedures, the weighting factor is 1. Dose limits for occupational exposures are expressed in equivalent doses for deterministic effects in specific tissues. It is measured in Sievert (Sv).

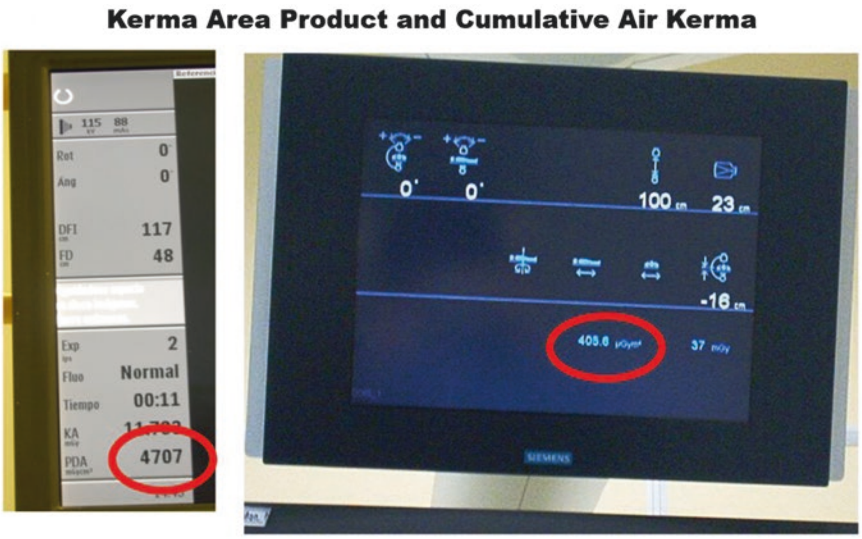


Fig. 3.1 Most of the interventional x-ray systems offer information of the relevant dosimetric parameters inside the catheterization room. In the figure, the values of the kerma-area product from two different systems are highlighted

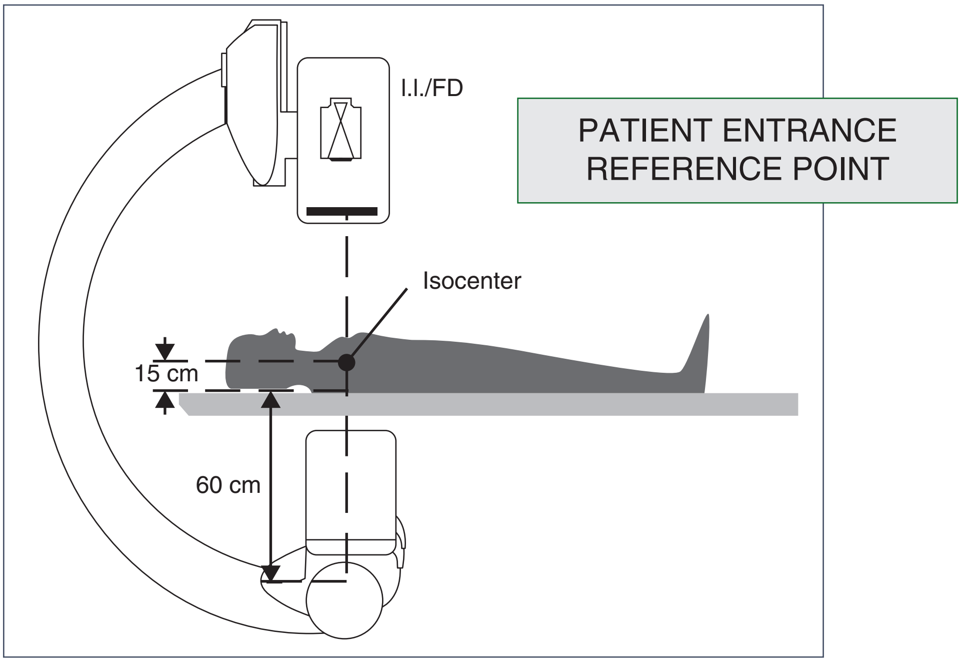


Fig. 3.2 Shows the position of the "patient entrance reference point" as defined by the International Electrotechnical Commission [24]. Below the patient and table is the x-ray tube and above the patient is the image intensifier, commonly called the II (pronounced eye-eye) (Reprinted with permission from Ref. [25])

Table 3.1 Tissue weighting factors recommended by International Commission on Radiological Protection (ICRP)

Tissue	w_r	$\Sigma\, w_r$
Bone marrow (red), colon, lung, stomach, breast, remainder tissues (nominal w_r applied to the average dose to 14 tissues)	0.12	0.72
Gonads	0.08	0.08
Bladder, esophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04

Adapted with permission from Ref. [26]

Remainder tissues (14 in total): adrenals, extrathoracic (ET) region, gallbladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix

- *Effective dose* measures the global risk of the person exposed to ionizing radiation and takes into account the equivalent doses in the different tissues and the radiosensitivity of that tissue (Table 3.1). This quantity is used to determine radiation exposure risk to cancer development. Dose limits for occupational exposures are expressed as effective dose for stochastic effects throughout the body [26]. It is also measured in Sievert (Sv).
- *Personal dose equivalent* is the operational quantity for individual monitoring and represented by Hp(d) (Fig. 3.3). It is the dose equivalent in soft tissue at an appropriate depth, d, below a specific point on the human body. The specified point is normally taken at 10 mm, termed Hp(10) for monitoring the effective dose. For the assessment of the dose to the skin and to the hands and feet, Hp(0.07) is used. A depth of 3 mm is adequate for monitoring the dose to the lens of the eye. In practice, Hp(0.07) and Hp(10) can be used for monitoring occupational doses during interventions guided by radiological imaging. A typical personal dosimeter provides two values, Hp(0.07) and Hp(10). Hp(0.07) from the collar dosimeter worn over protective garments (apron, thyroid shield) which provides a reasonable estimate of the dose delivered to the surface of the unshielded skin and to the lens of the eye. A single under-lead dosimeter does not provide any information about eye dose [27].

Summary of Biological Effects of Ionizing Radiation

The biological effects of radiation can be grouped into two types: deterministic effects (tissue reactions) and stochastic effects (cancer and heritable effects).

Key Points

Deterministic effects: Side effect occurs above a threshold radiation dose and severity increases with increasing dose.

Stochastic effects: Risk of developing side effect increases above a certain dose but the severity does not.

Deterministic Effects

Deterministic effects describe a relationship between radiation and side effects which occur above a certain threshold. With increasing doses above the threshold, the probability of occurrence will rise steeply to 100% (i.e., every exposed per-

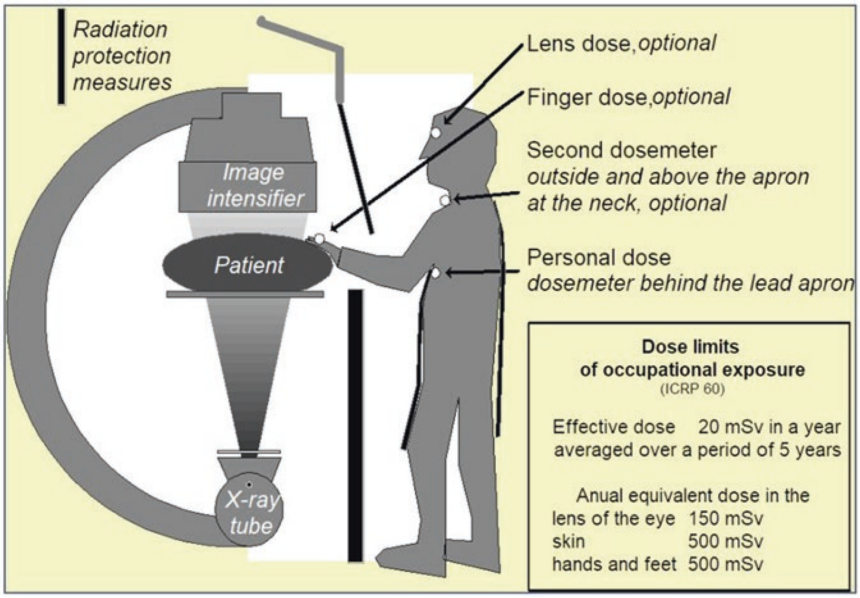


Fig. 3.3 Typical position of the personal dosimeters to estimate occupational radiation risk. The indicated dose limits (recommended by ICRP) are still valid except the one for the lens of the eyes than now has been lowered to a value of 20 mSv/year (Reprinted with permission from Ref. [1])

son will show the effect), and the severity of the effect will increase with dose. Such effects can occur in some complex interventional procedures [26, 28]. In FGIP, the tissues of concern for deterministic effects are the skin and the lens of the eye.

Stochastic Effects

There is good evidence from cellular and molecular biology that radiation damage to the DNA in a single cell can lead to a transformed cell that is still capable of reproduction. Despite the cellular repair mechanisms, there is a small probability that this type of damage can lead to a malignant condition termed the somatic effect. For stochastic effects, a simple linear non-threshold dose-response relationship is assumed for radiological protection purposes. At higher doses and dose rates, the probability of developing cancer increases. At even higher doses, close to the thresholds of deterministic effects (tissue reactions), the probability increases more slowly and may begin to decrease, because of the competing effect of cell killing. These effects, both somatic and heritable, are called “stochastic.” The probability of such effects is increased when ionizing radiation is used in medical procedures [28].

Effects of In Utero Irradiation

There are radiation-related risks to the embryo/fetus during pregnancy that are related to the stage of pregnancy and the absorbed dose to the embryo/fetus. At doses below 100 mGy, lethal effects are extremely infrequent, and there is no reason to believe that exposure will result in any fetal abnormalities. During the period of major organogenesis, conventionally taken to be from the third to the eighth week after conception, malformations can occur, particularly in the organs under development at the time of exposure. These effects have a threshold of approximately 100 mGy [28, 29].

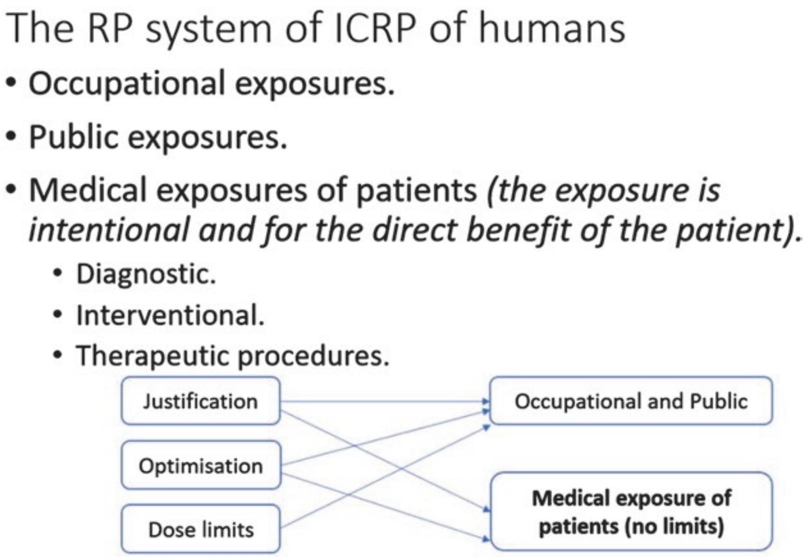
Key Points
Deterministic effects that occur above a threshold absorbed dose:

- Fetal abnormality: 0.1–0.5 Gy
- Sterility: 2–3 Gy
- Skin erythema: 2–5 Gy
- Hair loss: 2–5 Gy
- Lethality (whole body): 3–5 Gy
- Cataracts: 5 Gy
- Irreversible skin damage: 20–40 Gy

Radiation Protection System in Medicine

Several features of radiation exposure in medicine require an approach to radiation protection that is somewhat different from that for other types of radiation exposure. Medical uses of radiation for patients is voluntary in nature, with an expectation of direct individual health benefit to the patient.

In medicine, the goal is to use the appropriate radiation dose to obtain the desired image or desired therapy without



The RP system of ICRP of humans

- Occupational exposures.
- Public exposures.
- Medical exposures of patients *(the exposure is intentional and for the direct benefit of the patient).*
  - Diagnostic.
  - Interventional.
  - Therapeutic procedures.

Fig. 3.4 For medical exposures, only the principles of justification and optimization are applied. Dose limits only apply to the occupational and public exposures to ionizing radiation

excess exposure. In this regard, the ICRP introduced the use of diagnostic reference levels for imaging procedures. Radiation protection should be part of the quality assurance (QA) programs in interventional radiology (Fig. 3.4).

Radiation protection in medicine serves to identify the minimal dose for patients while allowing appropriate diagnosis or therapy and optimizing protection. The term ALARA (as low as reasonably achievable) is used to identify the optimization principle. ALARA is only part of the concept of optimization. The entire concept implies, more precisely, keeping patient exposure to the minimum necessary to achieve the required medical objective, both diagnostic and therapeutic. That said, dose to a patient should not be limited if effective diagnosis and treatment are imperiled. The physicians and other health professionals involved in the procedures that irradiate patients should always be trained in the principles of radiological protection, including the basic principles of physics and biology [17]. Physicians, radiographers, and medical physicists all play an essential role in the safe use of fluoroscopy in medical practice [30].

Radiation Protection of Patients (And Diagnostic Reference Levels)

Diagnostic reference levels (DRLs) are used in medical imaging to indicate whether, in routine conditions, the levels of patient dose from a specified imaging procedure are unusually high or low for that procedure. If so, a local review should be initiated to determine whether protection has been adequately optimized or whether corrective action is required [26].

DRLs should be reviewed at intervals that represent a compromise between the necessary stability and the long-term changes in the observed patient dose distributions [31, 32]. National DRLs should be set as the seventy-fifth percentile of median values obtained in a sample of representative centers. Median values of the DRL quantity for medical imaging procedures should be compared with DRLs to identify whether the data are substantially higher or lower than might be anticipated [32].

To protect a patient from excess radiation, the patient should be placed as far as possible away from the x-ray tube (portion underneath the table) and as close as possible to the image receptor (part above the table). Tight collimation also decreases patient dose and improves image quality by reducing scatter.

Key Points

“As Low As Reasonably Achievable” (ALARA) is based on the safety principle of minimizing radiation dose and limiting radioactive materials into the environment by employing all reasonable methods. The three major principles for a good protection are:

1. Time
2. Distance
3. Shielding

Radiation Protection of Staff (Including Pregnant Women)

There are different theories regarding possible dangers of exposure to personnel. It is extremely important to adapt the behavior and a safe working culture to the new powerful x-ray machines. Over time, longer procedures can lead to cumulative damage to our eyes if the proper protection is not regularly used. Reports on the radiosensitivity of the eye that can lead to visual impairment are available [33, 34].

In 2010, joint guidelines on protection of personnel were published by SIR (North American Society of Interventional Radiology) and CIRSE (Cardiovascular Interventional Radiology Society of Europe) in the Journals of both Societies (JVIR and CVIR) [20]. These guidelines provide a comprehensive overview that includes detailed instructions on why and how to protect IR from occupational exposure. These guidelines should become an integral part of any IR training program as well as routine practice in IR Labs.

Effective use of occupational radiation protection methods requires both appropriate education and training in radiation protection for all interventional radiology personnel and the availability of appropriate protective tools and equipment. Regular review and investigation of personnel monitoring results, accompanied by changes in how procedures are performed and equipment used, will ensure continual improvement in the practice of radiation protection in the interventional suite [35].

Passive and Active Personnel Radiation Protection

Personnel radiation protection process includes passive and active tools (Table 3.2). Passive radiation protection is based on the equipment in the IR lab. Active radiation protection is based on the passive protection tools and is about adapting our behavior to the “unfriendly” environment in the fluoroscopy room.

Active protection tools include protective drapes suspended from the table and from the ceiling. Table-suspended drapes hang from the side of the patient table, between the under-Table X-ray tube and the operator. They should always be employed, as they have been shown to substantially reduce operator dose.

Key Point

0.5 mm lead blocks approximately 95–99.5% of 70- to 100-kVp X-rays. Leaded glasses reduce exposure by a factor of 8–10.

It is not enough to have the protective tools available, but they must be used appropriately in order to safely protect all staff and patients within an interventional suite. The use of these tools must also be judged against their impedance to performing the procedure. Protective resources such as radiation protection gloves could lengthen the procedure in some cases and thus compromise the security and protection of the patient, as the tactile sensation of the catheter is reduced. In addition, the use of a leaded screen suspended from the ceiling could inhibit the movement of the C-arm x-ray system in some cases. Staff exposure drops dramatically with distance from the x-ray source. The inverse square law describes the proportional reduction in radiation density by the square of the distance.

Key Points

Inverse square law:The intensity of radiation exposure is inversely proportional to the distance from the source.

$$\text{Intensity} = \frac{1}{\text{distance}^2}$$

Table 3.2 Passive and active radiation protection equipment

	Examples	How to effectively use it
Architectural	Built into the wall	
	Rolling/ stationary shields	Stand behind shield when appropriate
Equipment mounted	Suspended from ceiling/ table	Should always be employed Cannot be used if C-arm is obliqued
	Disposable protective drapes	Can consider for long cases Adds cost
Personal protective devices	Apron	0.25 mm lead-equivalent with double protection (0.5 mm) anteriorly Worn at all times Should cover long bones of the body, down to the knees
	Thyroid shield	Wear around the neck at all times
	Leaded eyeglasses	Radiation cataract formation may be a stochastic effect Best with large lenses and protective side shields to minimize scatter
	Leaded gloves	Can be used when operators’ hands must be near but not in the radiation field. They do not protect when the hand is within the radiation field and can lead to a false sense of security

Hybrid rooms present additional radiation protection challenges [30]. Multidisciplinary teams of diverse staff members using different surgical and endovascular tools, imaging with fluoroscopy or DSA, cone beam CT, C-arm angulations, and isocentric positioning of the central beam create greater need for behavioral adaptation and increased awareness of radiation exposure. A small symphonietta should be orchestrated as these teams work shoulder to shoulder.

Personnel Dose Limits

The limit on effective dose for exposed workers should be 100 mSv in a consecutive 5-year period, subject to a maximum effective dose of 50 mSv in any single year. The limit on equivalent dose for the lens of the eye should be 150 mSv in a year. The limit on equivalent dose for the skin should be 500 mSv in a year. The limit on equivalent dose for the hands, forearms, feet, and ankles should be 500 mSv in a year. The current limit for the annual dose to the lens of the eye is 150 mSv, but recently based on the reports on the potential eye damages, the ICRP recommended about sevenfold less limit of 20 mSv/year for the eyes (or 100 mSv in 5 years with a maximum value of 50 mSv in a single year) [36].

Dosimetry badges are assessed periodically thus operators learn of their exposures in retrospect, sometimes weeks later. This delayed feedback may limit changes in staff habits. To better implement changes in work practices, it can be helpful for the individual to receive frequent feedback on dose levels through a real-time dosimeter. This may have a real impact radiation practice and influence behavioral change [37].

Pregnant Personnel

For pregnant workers, fetal dose is usually estimated using a dosimeter placed on the mother's abdomen, under her radiation protective garments. For women who may be pregnant, the ICRP recommends that the additional dose to the embryo/fetus does not exceed about 1 mSv during the pregnancy [26].The restriction of a dose of 1 mSv to the embryo/fetus of a pregnant worker after declaration of pregnancy does not mean that it is necessary for a pregnant woman to avoid work with radiation completely or that she must be prevented from entering or working in designated radiation areas. It does, however, imply that the employer should review the exposure conditions of pregnant women carefully [6, 22].

Particular Consideration for Pediatrics and Pregnancy

There are several important considerations for the pediatric population. UNSCEAR has recently published a new report of radiation risks for pediatrics [38] concluding that children may be at increased risk, the same risk or less risk than adults for development of malignancy depending upon the tumor type. The attributable lifetime risk of death (total cancers) in young children is higher than in adults, perhaps by a factor of 2 or 3. Appropriate weight bands are recommended by ICRP for establishing pediatric DRLs [38]. The settings and imaging protocols for interventional procedures in pediatrics require specific evaluation and regular updates for optimization [39].

Radiation exposure to both the patient and staff within the interventional suite when pregnant is an important and justified concern. In any circumstances involving the potential or actual use of fluoroscopically or CT-guided interventional procedures, a pregnant patient may be extremely concerned about the outcome of the pregnancy, and a counseling session with the mother (and father if possible) is often useful based on dose and risk to the fetus. If possible, pre-procedure and post-procedure counseling should take place [21].

Key Points

Limit of effective dose for exposed workers:

- 50 mSv max in a single year
- 100 mSv in a consecutive 5-year period
- 20 mSv equivalent dose to the lens of the eye, recently lowered from 150 mSv
- 500 mSv equivalent dose to the skin
- 1 mSv to fetus during pregnancy

Medical radiation procedures on pregnant patients should be justified and tailored to reduce fetal dose. Termination of pregnancy at fetal doses of <100 mGy is not justified based upon radiation risk [29].

Key Point

A pregnant female does not need to stop working in radiation areas; instead extra care should be taken to protect the fetus including extra shielding.

Radiation Protection in CT Fluoroscopy (CTF)-Guided Interventions

CT-guided procedures and particularly growing use of CT fluoroscopy (CTF) guidance are an important contributor to the patient, as well as operator, exposure. Careful management of CT scanner parameters is required. Combination of fluoroscopy and CT with real-time image control over the entire body has high geometric accuracy, no significant interfering artifacts, increased target accuracy, reduced intervention times, and improved needle visualization.

Practical Recommendations for a Good Practice Minimizing Radiation Risks

Radiation dose management requires a comprehensive approach including preprocedural planning, intraprocedural management, and postprocedural care. It also includes periodic quality assessment [40]. The informed consent process supplies patients with sufficient information to make an appropriate decision regarding the proposed procedure. Participation by the radiologist in the follow-up of patients at risk is an integral part of radiation dose management. Close follow-up, with monitoring and management of radiation-induced injury or referral to another specialist, is appropriate for the interventional radiologist [19].

Key Points

Steps for safe radiation practice [20]:

- Minimize fluoro time and number of spot images.
- Use available shielding, both personal and equipment.
- Use collimation.
- Plan the procedure ahead of time as much as possible.
- Position yourself in a low-scatter area.
- Obtain appropriate training.
- Wear your dosimeter and know your dose!

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