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THE ANGIOGRAPHIC ROOM

Size, Shape, Layout

The angiographic room must have sufficient space to house the fluoroscope and ancillary equipment as well as patient care, work, and storage areas. The minimum recommended size is 50 m^2 (500 ft^2) with a ceiling height of 3m (10 ft). Where possible, the bulky components that constitute the generator and its associated electronics should be in a well-ventilated but visually and acoustically isolated space. The architectural arrangement must meet cable length limitations and should permit unimpeded access between the procedure room and electronics area for installation and service purposes. Room lighting must be sufficient to facilitate each of the multitudes of tasks associated with an interventional procedure. However, the lighting should not interfere with optimum viewing of the fluoroscopic images (perhaps by switching from high-level to lower-level lighting when the x-ray beam is on).

The angiographic room requires appropriate structural radiation shielding. Specifications are based on the laboratory's anticipated workload, the nature of the occupancy of adjacent areas (including above and below), and local regulatory requirements. Structural shielding includes the doors to the laboratory and the observation window between the control and procedure rooms. Additional portable shielding may be required for gamma-brachytherapy, when performed. For radiation protection purposes, support personnel should work at a distance from the x-ray gantry and be positioned behind x-ray shielding (fixed lead or rolling lead-acrylic partitions) whenever not delivering direct services to the patient. An appropriately sized lead-shielded control room should be provided outside of the procedure room, housing instrumentation for patient monitoring. Design elements should optimize staff access as well as verbal and visual communications between the procedure and control rooms.

Gantry and Table

The centerpiece of the cardiac catheterization laboratory is the floor-mounted or ceiling-suspended gantry that holds the x-ray tube and the image intensifier in correct alignment and provides a full range of two-dimensional rotation (left to right anterior oblique) and skew (cranial to caudal) of the direction with which the x-ray beam passes through the patient. The two axes of rotation meet at a single point (the isocenter of the gantry), so that an object (the patient's heart) placed at that point in space will remain centered on the screen even as the beam direction is changed. The patient is supported in that position on an adjustable-height, flat-top table. The table top can be panned in the left-right or head-foot direction to move the patient relative to the x-ray beam.

A second complete imaging chain is provided in some laboratories to provide simultaneous viewing of cardiac structures from two angles. Biplane imaging is indispensable when indicated for certain patients and procedures, but is not required for most invasive cardiology procedures.

Other Equipment

The other piece of indispensable fixed equipment is the physiologic monitor (including an in-laboratory display). Means for electronically time-stamping and recording all events during the procedure may be included in the physiologic monitor's computer. Online access to old studies (images, reports, physiologic data) is often desirable.

Various additional fixed or mobile equipment is found in the modern laboratory, including defibrillators, ultrasound imaging systems, interventional devices, pulse oximetry and noninvasive blood pressure monitors. All such devices must meet patient electrical safety regulations, with specific rules for line- or battery-operated equipment that might come in contact with the patient (or anything conductive attached to the patient) under normal or emergency circumstances.

Equipment Quality Assurance

The proper functioning of the imaging equipment can be ensured only if it is tested on acceptance for compliance with its published specifications. Testing includes verification of compliance with local regulatory requirements as well as an evaluation of imaging performance and patient dose (16–18). Image performance and patient dose aspects of the protocol need to be rechecked on a periodic basis. The NEMA XR-21 phantom, jointly developed with SCAI (19) can serve as the basis for much of the constancy test protocol.

Images are viewed on any one of a variety of video displays (either CRT or LCD). These range from dedicated in-laboratory displays, through dedicated PACS workstations, to office PCs and laptops. Any display used for clinical decision making should be included in the laboratory's quality assurance protocol (20,21).

BIOLOGIC EFFECTS OF RADIATION (GENERAL)

The average person in the United States is irradiated by a variety of natural and human-made sources (Fig. 2.11), and radiation is arguably the best studied of all environmental

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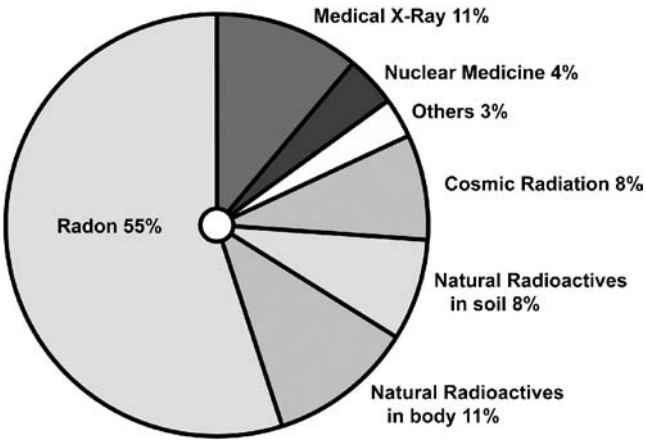

Figure 2.11 Average annual effective dose in the United States. More than 80% of the effective dose is delivered by natural sources. Medical use of radiation supplies most of the remaining amount.

"pollutants" (22–24). A typical annual effective dose equivalent from natural background, including radon, is around 3 mSv (300 mrem) (25,26). The actual amount of natural background varies depending on where individuals live, housing construction, and other factors. The major cause of human-made exposure is medical *imaging* (27). Presuming that radiologic imaging procedures are clinically justified and technically optimized, the expected clinical benefits of using radiation outweigh the radiation risks of the procedures. For the interventional staff, radiation exposure is a byproduct of the procedure, and the occupational dose received during all such procedures should be minimized to the extent possible without compromising appropriate patient care—referred to as ALARA (*a*s *l*ow *a*s *r*easonably *a*chievable).

Radiation injuries are induced by one of two mechanisms. The *stochastic* mechanism of action is caused by unrepaired radiation damage to the DNA of even a single viable cell. In contrast, the *deterministic* mechanism is caused by radiation acutely killing off large numbers of cells. Radiation management differs for these two mechanisms.

Stochastic Effects

The word *stochastic* is defined as involving chance or probability. Stochastic effects are presumably induced by a single photon causing unrepaired injury to the DNA of a single viable cell. Depending on their type, damaged cells can proliferate to produce a malignancy in the irradiated individual or a genetic disorder in future generations. The severity of the resultant injury, caused by propagation of a single (unrepaired) damaged cell, is independent of the dose that started the process (22, 24). But the linear nonthreshold (LNT) model often used for radiation protection calculations states that the probability of injury increases linearly with dose. Risk coefficients are small for radiation

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injuries, and direct evaluation of that risk at background radiation levels or even at levels corresponding to most imaging procedures is a statistical impossibility. Instead, the coefficients are obtained by looking at available popu- lations exposed to high levels of radiation (i.e., atomic bomb survivors) and extrapolating back to lower doses. Because manifestation of the injury requires cellular prop- agation, stochastic effects are typically seen years to decades after irradiation. Radiation-induced leukemia thus occurs between 2 and 25 years after irradiation, whereas solid radiogenic cancers have a latent period of 5 to 20 years.

Cancer

For the purposes of this chapter, the risk coefficients for cancer induction in staff and patients are 5 and 10% per Sv of effective dose (28). The difference between the two values is the presence of repair, which reduces the risk of an exposure if it is delivered over a lifetime rather than acutely. The patient coefficient applies to adults and is higher for pediatric patients and perhaps for procedures in which the premenopausal female breast is directly irradi- ated. The error bars in these estimates are as large as the values. Moreover, 1 Sv is quite a large radiation dose that would correspond to receiving a maximal occupational dose (5,000 mrem equals 50 mSv) each year for 20 years, and it is difficult to detect any increase in cancer rates above the significant cancer risk in the nonradiated popu- lation.

Heritable Abnormalities

The risk for radiation-induced heritable effects is also esti- mated to be less than 10% per sievert of dose delivered to the gonads (22). Interventional cardiac procedures seldom expose the gonads to significant amounts of radiation. Even this small risk is applicable only to patients who become future parents. Thus, the main concerns for radia- tion-induced genetic damage should be focused on pedi- atric and young adult patients. Patient risk can be managed by reducing total patient dose while minimizing pelvic irradiation. Staff risk is reduced by most actions taken to reduce staff dose.

Deterministic Effects

Deterministic effects occur when a significant number of existing cells are sufficiently damaged so as to cause observable injury. Immediate injury is either owing to mas- sive cell killing or a prompt biochemical tissue response to radiation. Delayed injuries become manifest when injured cells die without being replaced. The threshold dose for a deterministic effect depends on the fraction of cells that need to be killed before tissue loses viability, whereas the time course is dependent on the nature of the tissue and its

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TABLE 2.2
DETERMINISTIC INJURY THRESHOLDS

Effect: Single-Dose	Threshold (Gy)	Onset
Early transient erythema	2	Hours
Main erythema	6	~10 days
Temporary (permanent) epilation	3 (7)	~3 weeks
Dry (moist) desquamation	14 (18)	~4 weeks
Secondary ulceration	24	>6 weeks
Ischemic dermal necrosis	18	>10 weeks
Dermal atrophy (2nd phase)	10	>1 year
Late dermal necrosis	>12?	>1 year
Skin cancer	stochastic	>5 years

Food and Drug Administration. *FDA Public Health Advisory: Avoidance of Serious X-Ray-Induced Skin Injuries to Patients During Fluoroscopically Guided Procedures.* 1994 (see reference 37).

cellular kinetics. Table 2.2 reviews the threshold doses required to induce different effects and the time between irradiation and the emergence of the injury. The threshold doses apply to the entire dose being delivered in 1 day. Tissue can tolerate a greater total dose if the irradiation is divided over several sessions instead of being delivered at once, assuming that they are separated by enough time for repair to occur. The necessary time intervals are not well known and may range from a day to several months. Thus, the radiobiologic effect of skin irradiation cannot be predicted by simply adding the dose (delivered to the same skin area) from multiple procedures.(8)

Following moderate radiation doses, repair processes gradually replace nonviable cells with normal tissue or scar. Repair is seldom complete, and chronic radiation injury reflects incomplete repair. In that setting, the tissue (i.e., the patient's skin) may have a lower threshold than that shown for a single dose.

Patient Radiation Risks

Skin Injuries

Radiation-induced skin injury is the most common deterministic effect that occurs as a consequence of fluoroscopic procedures. Because the doses required to cause these injuries are large (usually >60 minutes of fluoroscopy time and entry doses >2 Gy), they are rare complications of invasive cardiac procedures. The Food and Drug Administration (FDA) has received about 100 reports, mostly as the result of electrophysiology ablations or complex coronary artery interventions. A severe skin injury obtained from the FDA web site is illustrated in Fig. 2.12. Many additional cases are reported in the literature (3,29–37). The skin at the site where the fluoroscopic beam enters the patient receives the largest radiation dose and is the organ at greatest risk.

Radiation-induced skin injury can usually be identified by the temporal pattern of its development in relation to the time of irradiation and by the location of the injury at the beam entrance site. If the beam is positioned over a single skin site for a prolonged time and the collimation is not changed, the lesion will be well demarcated with a square or rectangular shape consistent with that of the collimated beam. The appropriate management of several major injuries was delayed because the prompt erythema was initially attributed to other causes (e.g., allergic reaction to a defibrillator pad). If the patient fails to mention the x-ray exposure when a dermatologist is consulted, a skin biopsy may be performed resulting in a chronic nonhealing of the radiation-damaged tissues. The patient's state of health may modify the normal response of skin to radiation (30,35) with collagen vascular disease, diabetes mellitus, and hyperthyroidism making the patient more susceptible to injury. Various chemical and pharmaceutic agents have also been associated with increased risk for skin injury.

Because of incomplete repair, patients who have previously undergone fluoroscopically guided procedures or radiation therapy may have a lower threshold for radiation injury in subsequent procedures. The literature reports several cases of chronic skin changes associated with multiple procedures irradiating the same portion of skin (3,36). Such factors need to be considered when planning a follow-on intervention.

Induced Neoplasm in Adults

A typical diagnostic coronary angiogram (DAP of 40 Gy/cm^2) will deliver approximately 8 mSv to the patient (38–40). The resultant cancer risk is likely to be less than 0.1%. The cancer risk resulting from a complex intervention in a heavy patient (DAP of 200 Gy/cm^2) is unlikely to be increased by as much as 1%. By way of comparison, a

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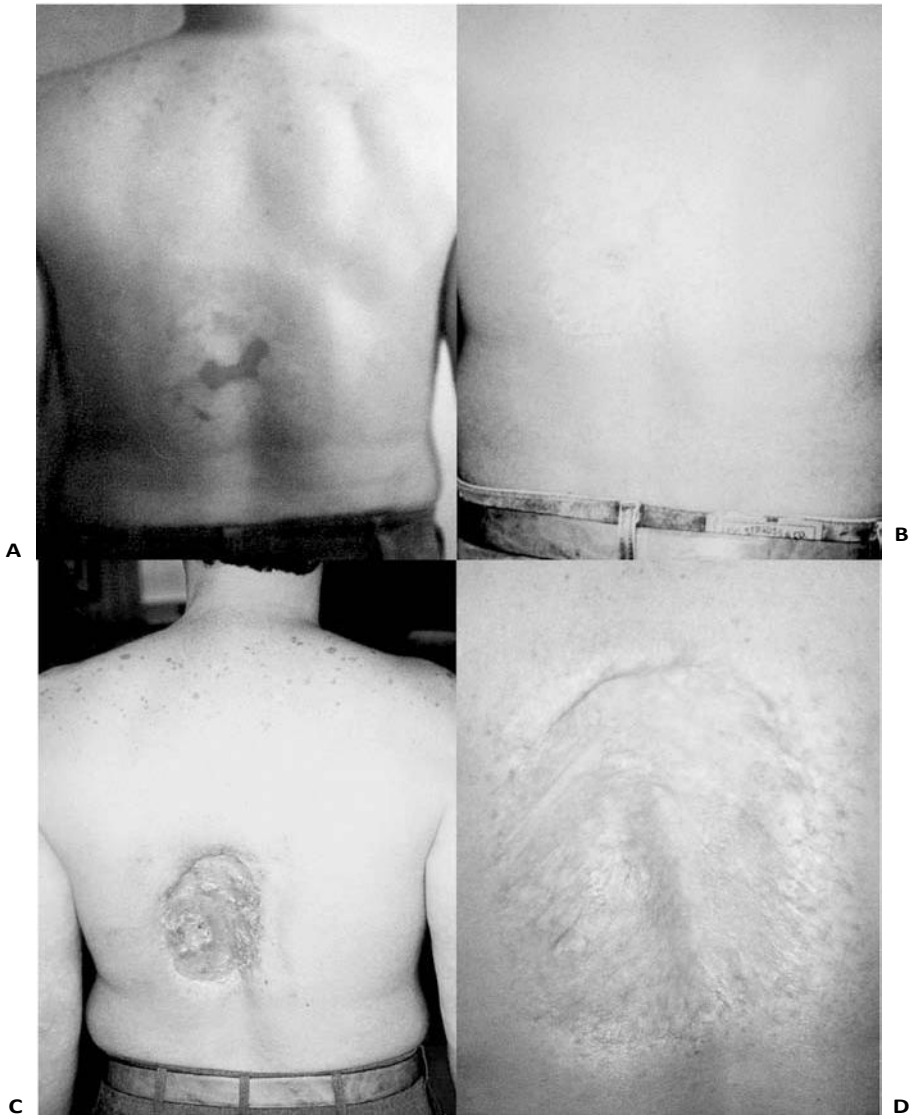

Figure 2.12 Time line of a major radiation injury (Reference 1). Early erythema and blistering at approximately 8 weeks is seen in **(A)**. This has resolved by approximately 20 weeks **(B)**; however the tissue is necrotic. The tissue has broken down by 20 months **(C)**. A skin graft was required **(D)**. A fuller explanation of this sequence is available in a 1995 publication at http://www.fda.gov/cdrh/rsnaii.html (last accessed 17 Mar 05)

60-year-old cancer-free male with no special risk factors has a 16% probability of being diagnosed with cancer in the next 10 years of his life. The stochastic risk of neoplasm from an invasive procedure is thus small in comparison with the natural incidence of cancer.

Risk of Neoplasm in Children

Radiation risk management in children is different than that for adults. Radiogenic neoplasm is importantly related to age at exposure and is gender dependent (22). Females are more susceptible than males because of greater breast and thyroid sensitivity. Additionally, because of a smaller body, a greater portion of a child's radiosensitive tissues are in close proximity to the x-ray beam during cardiologic

procedures. Fortunately, because of the small body, radia- tion penetrates small children more readily, so dose rates and total doses are relatively low. Caution is indicated when working with almost-adult-size children.

The Pregnant Patient

Radiation risks associated with pregnancy are thoroughly reviewed elsewhere (41). At low fetal doses, the principal risk is radiation-induced cancer. The lifetime risks induced by an in utero exposure are likely to be similar to the new- born risk. Fetal doses >100 mSv place the child at risk for deterministic effects such as central nervous system dam- age, growth retardation, malformation, or miscarriage. The specific risks are determined by actual fetal dose and

gestation age. Fetal doses in this range seldom happen unless the uterus is directly irradiated.

Fluoroscopic procedures on pregnant women may be justifiable in an emergent situation. Procedures that involve structures above the diaphragm are unlikely to induce fetal deterministic effects (malformations), because direct irradiation of the fetus can usually be avoided and the fetus then receives only radiation scattered from the irradiated area. The carcinogenic risk to the child is the principal concern, and this risk must be weighed in relation to the anticipated clinical benefits to the mother. Minimizing the total use of radiation, applying good collimation, and avoiding unnecessary direct irradiation of the uterus during pregnancy contribute to minimizing fetal injury. Protective measures including avoiding extreme cranial angulations and using an arm approach reduce fetal radiation risk. A consultation with a medical physicist regarding fetal dose management prior to the procedure can be helpful.

Patient Radiation Management

Radiation-induced injury must be considered in the overall risk–benefit decision making process. How much radiation can be safely used before stopping? What are the benefits of splitting a procedure? Several factors enter into the decision of stopping or continuing a procedure: These include an adequate knowledge of the pathophysiology of radiation, appropriate patient consent, information on prior radiation usage, and the clinical requirements for continuing the procedure.

The quantity of radiation used in a simple diagnostic study performed on an average-sized patient is well below the threshold of deterministic injury or significant stochastic risk. But radiation dose increases with increasing complexity and patient size and may increase these risks to reach clinical significance. Under these circumstances the operator should proceed with caution, and only if the operator is certain that proceeding is essential to the patient's health and no other practical alternatives exist.

Equipment and Technique Selection for Dose Management

Equipment features and user-selectable operational modes provide fair control over x-ray dose rates. Operators should thus know the location and function of available dose management controls on each piece of equipment that they use and use them as needed to ensure minimal patient and personnel exposure. Common operator-selectable parameters include fluoroscopic pulse and dose rate and acquisition frame rate. Other factors may or may not be under the operator's control, including acquisition dose rate, x-ray beam energy (kVp), and beam filtration.

Images generated at lower dose per frame and at lower frame rates can be of lesser absolute quality, but may still

be sufficient for clinical needs (42). However, too low a dose or frame rate may paradoxically increase total dose. This is because increased irradiation time is needed to allow the operator to make clinical decisions. The lowest total-dose operating conditions that meet procedural requirements should be selected.

Different types of imaging equipment are available in most laboratories. The operator should have sufficient knowledge of the equipment's dosimetric characteristics to select the most appropriate room for each patient. For example, a laboratory equipped with a large FOV image intensifier (needed for peripheral procedures) is less dose efficient at cardiac FOVs than a dedicated cardiac labora- tory. The operator should consider another available labo- ratory if the use of substantial amounts of radiation is probable.

Effects of Patient Size on Patient Dose

As patient size increases, the input dose of radiation required for sufficient penetration of the x-ray beam through the patient to the image receptor increases rapidly. In most systems, increased penetration is achieved by using a higher kVp. This results in lower primary image quality because of reduced subject contrast. Large patients also generate more scattered radiation. This degrades image contrast and signal-to-noise ratio. The reduced image qual- ity may increase the procedure's technical difficulty, poten- tially prolonging it and consequently requiring an even greater total radiation input.

Positioning of the Gantry Relative to the Patient

It is convenient to perform a coronary interventional pro- cedure with the target lesion located at the fluoroscopy unit's isocenter. This minimizes the need to reposition the patient when the x-ray projection angle is changed. However, this strategy often shortens the distance between the x-ray tube and the patient, increasing the patient's entrance port skin dose. On the other hand, positioning the x-ray tube too far from the patient entrance may require an excessive increase in beam kVp, potentially degrading image quality. Where clinically possible, the beam angulations should be changed during a long inter- vention to minimize the irradiation of any particular por- tion of the patient's skin.

Beam Collimation

Collimating the x-ray beam to less than the working FOV is an important radiation management technique. Although this maneuver does not reduce skin dose per se, it does decrease the total radiation load on the patient. Less scat- ter is produced in comparison to an uncollimated beam. This has two beneficial effects: Image quality is improved and less scatter by the patient reduces staff exposure. The

semitransparent lung shutter provides similar benefits: Image burnout over the lung is reduced when it is used, and the total radiation flux reaching the patient is reduced, thereby reducing scatter with a consequent reduction in staff exposure.

Clinical Dose Monitoring

Intraprocedural radiation dose monitoring is a responsibility of the operating physician. The operator needs to be aware of beam orientation, x-ray field size, and output dose rates to achieve this goal. By way of analogy, the use of radiation should be monitored and managed as well as the dose of iodinated contrast agents. The goal of intraprocedural dose monitoring is to avoid unintentionally crossing of deterministic dose thresholds for the skin. Ideally, this can be accomplished by displaying a real-time map of the dose distribution on the patient's skin, but no technologies are commercially available to provide an accurate real-time display of peak skin dose (43,44).

Instead, catheterization laboratories have traditionally relied on fluoroscopic time as a primary dose measure. Although this was of marginal value for diagnostic studies, it is a very poor clinical metric in the interventional era, since it does not account for cine usage or the variations in x-ray output attributable to patient size or other variables (45). Most interventional fluoroscopic systems are now equipped with DAP meters, which can be used to estimate skin dose, but DAP readings do not account for the distance between the x-ray tube and the patient's skin nor for beam motion during the procedure. Systems compliant with the IEC interventional fluoroscopy standard are equipped with a cumulative dose monitor. This instrument reports the cumulative dose delivered during a procedure to a reference point defined relative to the x-ray system. It is at its most accurate when the beam does not move and the reference point coincides with the patient's skin. Intraprocedural and patient follow-up trigger levels based on cumulative dose have an improved correlation with peak skin dose. Laboratory policies should use this metric if it is available.

Incorporating dose monitoring results into the laboratory's continuous quality improvement (CQI) program is beneficial, because periodic review of all dose data will yield important information regarding equipment and operator performance. This information can be used to improve both equipment and operator dose efficiency.

Considerations Regarding Multiple Procedures

Dose fractionation reduces the deterministic risk of a given total radiation dose. However, the LNT model states that stochastic radiation risk depends on the total dose accumulated by a patient during his or her lifetime. Thus the cancer risk is presumed to increase with each additional procedure.

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Patient Education, Consent, and Follow-up

It is appropriate to include the possibility of radiation injury when obtaining informed consent from a patient who is at increased risk. Such patients include those who are expected to undergo a particularly long complex proce- dure, a patient who has had multiple recently performed procedures, or a patient who is extremely obese. An appro- priate postprocedure discussion and follow-up plan is applicable to all patients where substantial amounts of radiation were used. A combination of patient size and available dose measuring tools can be used to establish a follow-up policy that is likely to detect significant injuries. In high-dose patients; rashes appearing within 30 days or so at the beam entry point should be presumed to be radiogenic, and the interventional cardiologist should take an active role in arranging appropriate follow-up for all such cases.

Staff Radiation Safety

Staff radiation safety has a different benefit–risk analysis than patient radiation safety (46). Acute deterministic effects (cataracts, skin burns) should never happen in an interventional setting, because the operator should never be in the primary beam and should receive scattered radia- tion exposure only. There are a few reports of chronic deterministic effects (e.g., hair loss on the legs below the lead apron) in individuals who have spent decades in the laboratory, but future occurrences of these effects can be avoided by extending the basic principles of radiation protection discussed in this section.

Cancer induction is a topic of real concern to staff mem- bers. But repeated studies of radiation workers of all types, including interventional cardiologists, over the last 30 years have produced only anecdotal reports with no con- firmed evidence of increased cancer incidence in these populations (47–49). Nevertheless, interventional staff members are clearly exposed to radiation in the course of their duties, and the LNT model predicts a small increased risk of which workers should be aware.

Stochastic Risk

Staff stochastic risk is a function of the effective dose actu- ally received by a staff member. (This reflects the whole- body dose and not the raw reading from a film badge worn outside the lead apron (50))! The most highly irradiated operators in a properly functioning interventional labora- tory probably receive an effective dose of a few mSv/year. Most lab staff receive <1 mSv/year. By way of comparison, the natural background radiation level in Denver exceeds that in New York City by about 1 mSv/year. With a risk of fatal cancer estimated at 4% per sievert of exposure (even without considering the effect of appropriate shielding), the allowable occupational dose of 50 mSv/year would add

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only a 0.2% per year increment (to the background 20% spontaneous incidence) of developing a fatal neoplasm.

Staff Deterministic Injury

Acute deterministic effects (cataracts, skin burns) should never happen in an interventional setting. Nevertheless, radiation cataracts have been recently reported (51). Routine cinefluorographs documenting the operator's hand are seen with some frequency. Such incidents are almost always owing to poor understanding and technique as well as violations of the basic laws of radiation protec- tion. The lens of the eye has been reported to be relatively insensitive to radiation. In a well-documented study of the effects of low-voltage radiation therapy treatments of the head and neck (52), the cataract threshold was demonstrated to be 2,000 mSv for a single exposure, rising to 4,000 mSv for a 30-day course of therapy. At the present regulatory limit for eye exposure of 150 mSv/year, it would take more than 25 years of dose accumulation at the regulatory limit to exceed the 30-day threshold. However, a very recent preliminary study has shown evi- dence of lenticular changes at lower levels, and use of eye shielding (lead glasses or a portable lead-acrylic shield) should be considered.

Basic Principles of Reducing Staff Radiation Exposure

Most patients undergo only a few catheterization studies in their lifetime, but staff have daily exposure. The operator can use several methods to reduce his or her exposure to radiation (53–57), the most important of which is to min- imize patient dose—the ultimate source of exposure of the operator and staff. One of the most important means of reducing radiation exposure is reducing the amount of flu- oroscopy and cine time to the clinically required mini- mum. It is important to avoid the "lead foot" syndrome; the operator must learn to depress the fluoroscopy pedal briefly when it is necessary to confirm a catheter position and to reflexively take his or her foot off the pedal when- ever looking away from the television monitor. Similarly, cineangiographic runs should be selected carefully to show important findings, and each run should be terminated as soon as the necessary information is recorded.

The other cardinal measures used to reduce the operator's x-ray dose are *increasing distance* and the *use of shield- ing*. The operator should stand as far from the beam as pos- sible to take advantage of the inverse square law—one or two steps farther away from the x-ray tube may cut the dose in half. A wraparound apron should be provided to indi- viduals in the laboratory who have occasion to turn their back toward the patient. A wide variety of designs, materi- als, and lead thicknesses are available for tailoring radia- tion garments, but 0.5 mm lead equivalent provides roughly 95% shielding from diagnostic x-ray scatter.

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Additional radiation protection can be gained from wear- ing separate thyroid collars and wraparound leaded eye- glasses. Too much lead is detrimental to the operator's musculoskeletal system, but pull-down and table-side shields serve to protect the staff from radiation without the necessity of wearing heavy lead.

Laboratory staff needs to know when radiation is being produced. Modern digital systems give few clues in this regard. A "beam on" light is often installed in the proce- dure room. This is helpful if it can be seen. Oftentimes, the nurse is asked to attend to the patient's needs during a pro- cedure. These duties can occur in a potentially high radia- tion zone, and the operator should refrain from irradiating when staff is close to the patient.

Effect of Beam Orientation

This is particularly important during angulated shots such as the left lateral or left anterior oblique cranial projec- tions, which place the operator in close proximity to the beam entry point (Fig. 2.13).

Staff Radiation Monitoring

There is no substitute for having each operator measure his or her own exposure (58–61), and a radiation monitor should be worn at all times when working in the cardiac catheterization laboratory. A collar badge should be worn on the left shirt collar outside the lead apron. This gives a good measurement of eye exposure. Current recommenda- tions also call for a second waist badge, which is worn on the operator's belt just beneath the lead apron. These two badges should be of different colors (e.g., red for the collar and yellow or green for the waist) to avoid misplacement. Standard formulas allow an estimate of effective dose for the one- and two-badge cases. Each month, badges should be turned in for processing and replaced with fresh units. The resulting reports should be reviewed to confirm that no individual's collar badge dose exceeded 1 mSv/month (100 mrem/month) without further investigation. These dose levels should be observed only on busy operators. Recorded doses need to be studied regularly to ensure that occupational exposures remain below the prescribed limits.