Factors affecting radiation injury

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Introduction: **During the past several decades, the number of diagnostic tests and procedures that require the administration of radiation has increased dramatically. Understanding which factors affect radiation injury and how to mitigate these to protect patients has become critical for physicians to understand. Informed consent for these procedures has to include a discussion of the risks of radiation.**

Methods: **Factors that affect radiation injury, as well as ways to mitigate these, are discussed. Informed consent is also reviewed.**

Results: **Technical factors of the radiation delivery and patient factors both influence the dose of radiation received. Minimizing exposure is critical, and close examination of the patient is warranted to diagnose radiation injury. True informed consent includes a frank discussion of the radiation risks as well as the benefits of the procedure.**

Conclusion: **Minimizing patient radiation exposure and accurately diagnosing radiation injury are key skills with which any physician ordering or performing tests or procedures requiring the use of radiation needs to be familiar. Informed consent includes a discussion of the risks as well as the benefits of the proposed radiation exposure. (J Vasc Surg 2011;53:9S-14S.)**

One of the most famous pioneers in the field of radioactivity, Marie Curie, led a productive and prolific career that not only led to significant scientific advancements but also laid the foundation for medical usage of various radioactive elements. How ironic that after years of study of radioactivity, the aplastic anemia that claimed her life was ascribed to the prolonged exposure to radioactive agents. In fact, many early pioneers in this field suffered adverse medical effects due to overexposure to radiation.[1] Over time, many changes have occurred to mitigate the harmful effects to both patients and the medical staff who daily work with these hazardous materials. With the proliferation of fluoroscopic procedures, the risk of continued exposure to radiation has become a major concern among vascular surgeons. Cancer, development of cataracts, and impaired fertility are among the effects of prolonged radiation exposure.[2]

An understanding of the harmful effects of radiation exposure and the methods used to minimize them first requires an understanding of the factors that affect exposure and injury. A list of factors that affect exposure and injury is presented in Table I.

DOSE AND TIME

Overall, the risk of injury from radiation exposure is a function of the doses received by the patient and staff, which is in part a function of the type of equipment used, the mode of operation, and the time of exposure. It has been stated that "the single most important determinant of patient and staff radiation dose" is the time the fluoroscopy operator has his or her foot on the pedal.[3] This is a key concept—fluoroscopy operators have a tendency to forget to let up on the pedal during review of images. In addition, certain maneuvers, such as removal of wires or catheters, can often be accomplished by periodic "spot" use of fluoroscopy rather than having one's foot on the pedal constantly. Operators should never forget the "ALARA" concept: radiation workers should strive to use doses that are "As Low As Reasonably Achievable."[4]

MODES OF OPERATION AND POSITION OF THE IMAGE INTENSIFIER

Manual and automatic modes. Modern fluoroscopy equipment operates in the manual or automatic brightness control mode, sometimes referred to as the automatic exposure control mode. In manual mode operation, exposure rates are determined by factors set by the operator, including peak kilovolts (kVp), milliamperes (mA), and image field size. In general, higher exposure rates are generated by lower kVp, higher mA, and large image field size. In the more commonly used automatic brightness control mode, the factors are set by the machine to produce the appropriate image brightness. Brightness is detected by the image intensifier; the further the image intensifier is from the patient, the less bright the image appears. The image intensifier will first increase the kVp, but then also increase the mA, resulting in significantly increased radiation doses to the patient. It is important to keep the image intensifier as close to the patient as possible.[4]

Normal operating and high dose modes. Some types of fluoroscopy equipment have two radiation dose modes: normal operating mode and high dose mode. Normal operating mode is limited to <10 roentgen (R)/min. High dose fluoroscopy allows exposures rates of up to 20

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Table I. Factors that affect radiation exposure and injury to vascular surgery patients

Dose and time
Modes of operation and position of the image intensifier
• Manual vs automatic modes
• Normal operating vs high dose modes
• Continuous vs pulsed fluoroscopy
• Last image hold
• Field of view (collimation and magnification)
Additional patient factors
• Patient size
• Angulation of the x-ray unit
Distance and scatter
Cumulative/prior exposure
Positioning of portable C-arms

R/min for better penetration of tissue and improved image quality, but at the expense of increased radiation exposure. This mode should be reserved for procedures requiring very high levels of detail.[5]

Continuous vs pulsed fluoroscopy. Continuous fluoroscopy is a dynamic imaging technique in which the patient is continuously radiated to monitor the system of interest. A camera then displays the images at 30 frames/s. The limit is 10 R/min. This exposes the patient to much greater doses of radiation than pulsed fluoroscopy, in which the x-ray generator emits short bursts of x-rays. Using pulsed fluoroscopy not only decreases the exposure time to the patient but also has the added benefit of decreasing blurriness of the image from patient motion. Of note, if the pulse rate is increased to approximately 30 pulses/s, the dose rate is virtually equivalent to that of continuous fluoroscopy.[6]

Last image hold. Modern fluoroscopic equipment automatically includes "last image hold," which is now a requirement of the U.S. Food and Drug Administration.[5] When the fluoroscopy operator's foot is removed from the pedal, the last image is preserved on the image intensifier to allow for review.

Field of view (collimation and magnification). The larger the field of view, the more exposure the patient and staff receive. Closing the collimators will reduce this exposure and has the added advantage of producing a sharper image. Image sharpness can also be improved by electronic magnification, which is accomplished by using a smaller field of view from the image intensifier. With typical fluoroscopic machines, the operator can set the field of view to 12 inches (no magnification), 9 inches (some magnification), or 6 inches (most magnification). In automatic modes, however, the image intensifier will increase the radiation dose to maintain image brightness and quality.

Geometric magnification is a term used to describe magnification obtained by moving the image intensifier away from the patient. Geometric magnification results in increased doses to the patient, increased scatter of x-rays to staff (discussed below), and a reduction in image quality. This technique should be avoided.[7]

ADDITIONAL PATIENT FACTORS

Patient size. Penetration by x-rays of thicker body masses such as in obese patients requires higher radiation doses. The radiation dose inside tissues is reduced by a factor of two for every 4.5 to 5.0 cm of depth; therefore, twice as much radiation is required to penetrate 10 cm of subcutaneous fat than 1 cm. Thus, dose rates in obese patients can be as much as 4 to 10 times higher than in thin patients. In general, fluoroscopy units will automatically adjust the dose to achieve a certain level of brightness on the image intensifier, and the operator may be unaware of how great the doses are that the patient is receiving. This can result in thermal injuries to the skin, most often reported in obese patients.[6]

Angulation of the x-ray unit. The use of steeply angled projections has the same effect as obesity: the machine detects a much thicker tissue path and increases the dose to maintain penetration and an appropriately bright image. These projections should be used sparingly, particularly in obese patients.[7]

ADDITIONAL FACTORS AFFECTING STAFF EXPOSURE (DISTANCE AND SCATTER)

As x-rays exit their source, they travel in straight but divergent directions. Because divergence increases with distance, there is an exponential decrease in the number of x-ray photons per unit area as the distance from the source increases. This relationship is described by the inverse square law, which states

$$X = 1/d^2$$

Where X is exposure and d is distance.[8] Doubling the distance from the x-ray source results in decreasing the exposure by one-fourth. Tripling the distance results in decreasing the exposure by a factor of nine. Fluoroscopic operators and staff can reduce their exposure accordingly by moving away from the x-ray source.[8]

X-rays that enter a patient can be absorbed by tissue, exit the patient, and enter the image intensifier, or be partially absorbed and change direction. X-rays that exit the patient after changing direction are termed "scattered" x-rays. Scatter increases with increasing beam size, high kV and mA, wide-open collimators, and large distances between the x-ray tube and the image intensifier. At a 90° angle and 1 meter from the patient, the scatter is 0.1% of the intensity of the beam entering the patient. To some extent, the inverse square law can be used to calculate the effects of scattered x-rays on personnel. Maneuvers such as closing the collimators and placing the image intensifier close to the patient will reduce the amount of scatter, and moving away from the patient and table will reduce the amount of exposure to personnel.[9]

Cumulative and prior exposure. There is growing concern that the increased use of x-ray examinations, including multiple computed tomography scans and fluoroscopic interventions, may lead to cumulative radiation exposures that place patients at increased risk for cancer development. This is discussed more fully in the article in this supplement "Radiation exposure of vascular surgery patients beyond endovascular procedures," by Dr Zhou.

Special issue regarding the use of portable C-arms. Portable C-arm fluoroscopes can allow positioning of the x-ray tube close to the patient's skin. Operators should take special care to ensure that the tube is placed as far from the skin as possible, while the image intensifier is placed as closely as possible.[7]

INFORMING RISK

Informing health care personnel about risks of occupational exposure. With respect to the risk to health care personnel, the safe occupational environment begins with education. All personnel directly and indirectly involved in a radiation-exposed environment should understand the safe use of material and equipment, as well as the use of personal protective equipment. Furthermore, all health care personnel should be aware that the International Commission for Radiation Protection (ICRP) has published guidelines for the maximum dose limit for occupational exposure in a given year. These limits give guidelines for the whole body (20 mSv/y), the lens of the eye (150 mSv/y), and extremities outside of the lead apron (500 mSv/y).[10] Health care personnel should monitor exposure regularly and be aware of limits so that they can change practice if dose limits are reached.

Exposure to personnel performing endovascular techniques has been investigated by many authors. Lipsitz et al[11] compared the yearly exposure of the surgeon, first assistant, and second assistant performing endovascular procedures. The exposure of all operators was within the recommended maximum dosage limits. The maximum dosage was absorbed by the primary operator, and was 69% of the ICRP occupational dose limit.[11] Other groups have made similar findings; however, it should be acknowledged that the proportion of endovascular procedures and the volume of endovascular practice will vary widely between operators.[11-13]

Radiation exposure to health care personnel correlates directly to the dose area product (DAP) for the patient; thus, DAP provides a good surrogate measure of exposure.[14] This is useful because, unlike effective dose which requires calculation, the DAP is measured by most modern fluoroscopy equipment. However, personnel exposed routinely or who work near the radiation source should wear dosimeters to track their exposure and to be sure that it does not exceed 20 mSv/y.[10] The use of two dosimeters (one at the neck and the second under the lead shielding at the waist) may offer great measurement accuracy and is recommended by ICRP. The effective dose calculated for the physician may be overestimated when only one dosimeter, worn outside of the lead apron, is used, although some authors have recently refuted this belief.[15] The drawbacks of using a double dosimetry system, including cost, the frequent unintentional exchange of the two dosimeters, and the need to coordinate simultaneous replacement, make the single system more appealing.

Table II. Effective dose for different vascular interventional procedures

Procedure	*Effective dose (mean or range)*
Renal stenting	42 mSv[19]
	1.3-39.1 mSv[20]
	10.29 mSv[21]
Iliac stenting	17 mSv[19]
Lower extremity stenting or angiography	12 mSv[22]
	3.9-16.8 mSv[23]
Infrarenal aneurysm repair	10.5 mSv[24]
Aneurysm repair, including branched grafts	27 (16-117) mSv[25]
Abdominal computed tomography scan	10 mSv[26]

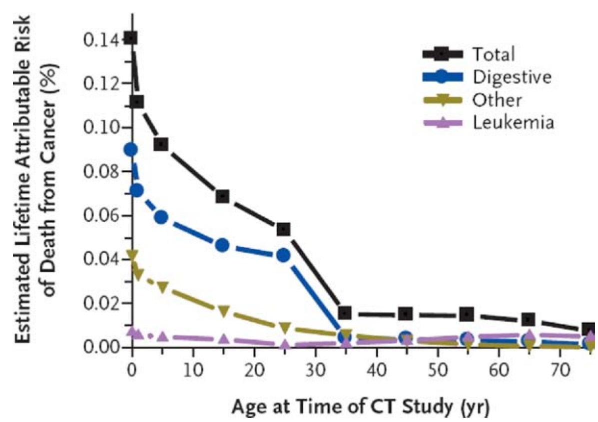

Fig. Lifetime risk of cancer based on age at first exposure to the radiation from an abdominal computed tomography (*CT*) scan. Reprinted with permission from Brenner et al.[27]

Follow-up for health care personnel. Health care personnel who are routinely exposed to x-rays during the course of their occupation should be aware of the risks and undergo routine medical assessment. Precise guidelines or a schedule for this clinical evaluation have not been established and thus should be based on an assessment of exposure and expected risk. Literature pertinent to the medical follow-up of persons who have been exposed to radiation in their occupational environments has been produced by industry. The exposure described in these articles is often much higher than one would expect to be present in the health care scenario.

One group responsible for the development of a medical examination program for workers at the U.S. Department of Energy National Laboratory suggested that persons exposed to ionizing radiation in the workforce should be screened with complete blood count, thyroid-stimulating hormone serum level, and chest radiograph.[16] The authors acknowledge that these recommendations are based on consensus rather than on data. Certainly the risk of developing cataracts would also warrant routine eye examinations; however, there are no published recommendations. Incumbent in the health care professionals who are

Table III. Deterministic effects of ionizing radiation

Effect	*Threshold dose (Gy)*	*Time of onset*	*Biologic mechanism*	*Clinical features*
Early transient erythema	2	24 to 48 hours	Increased capillary permeability and proteolytic enzyme release	Sunburn-type area matching shape of x-ray beam
Main erythema	10	10 to 28 days	Secondary inflammatory damage arising from damage in the basal cell layer of the epidermis	Burning, itching, and tenderness
Temporary epilation	3	Manifests after 3 weeks, with regrowth after 8 to 12 weeks	Depletion of the germinal layers of hair follicles	Regrown hair may by thinner with different pigmentation
Permanent epilation	7	Manifests after 3 weeks, but there is no regrowth	Permanent loss of the germinal layers of the hair follicle	
Hyperpigmentation	10	Manifests after about 1 month; usually fades but sometimes persists indefinitely	Melanocyte hyperstimulation	Sometimes melanocyte death results in variegated areas of hypo- and hyperpigmentation
Dry desquamation	14	Occurs about 1 week after main erythema	Damage to proliferating basal cells of the epidermis	Main erythema progresses to scaling and flaking of the stratum corneum
Moist desquamation	18	Occurs about 1 week after main erythema	Severe damage to proliferating basal cells of the epidermis	Main erythema progresses to blistering, skin sloughing, and continuous serous discharge; requires topical antibiotics and sterile dressings
Secondary ulceration	24	Occurs in the weeks and months after moist desquamation	After desquamation, epithelial regeneration occurs; endothelial swelling leads to arteriolar obstruction and an area of relative ischemia, vulnerable to secondary ulceration arising from minor trauma	Healing is delayed and the developing epidermis is usually very delicate
Late erythema	15		Late hyperemia	Mauve skin discoloration
Ischemic dermal necrosis	18	Occurs after 10 to 16 weeks	Microvascular damage causing progressive dermal ischemia and ulceration	Follows severe main erythema
Dermal atrophy				
First phase	10	Commonly follows main erythema and moist desquamation	Hypoplastic dermis and thin epidermis	Loss of hair follicles and scattered melanin deposits give the skin a poikilo dermatic appearance
Second phase	10	Appears after 1 year	Damage to the dermis	Slowly progressive; usually stabilizes after about 4 yrs
Induration			Epidermis and subcuticular adipose tissue replaced by fibrosis	Skin feels wooden and tender; if near a joint, it may restrict movement; patient may try to avoid moving the affected area
Telangiectasias	10	Appear in the first year	Atypical dilation of superficial dermal capillaries	Tend to increase over time
Late dermal necrosis	12	Peaks in 3 to 4 years	Avascular dermis is unable to support the atrophic epidermis	May occur without any history of moist desquamation

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using radiation increasingly as a means of therapy for endovascular surgery is the need to begin developing appropriate screening examinations and schedules to ensure that the workforce is not exposed to radiation levels leading to short or long-term health problems.

Informing patients about risks of radiation exposure. Distinguishing between diagnostic and therapeutic or interventional procedures is important when patients are informed about the risk of radiation exposure because the longer interventional procedures can increase the risks. As with health care personnel, education is a very important part of informed consent for radiation exposure to patients. Patients should be informed that obesity is a risk factor for radiation dose because exposure increases with increasing body mass index.[9,17] Because this is a modifiable risk factor, consideration should be given to postponing radiographic intervention if weight reduction is possible.

Radiation dose varies with the level of skill and experience, so providing information about the operators' own experience is also important in an informed consent discussion.[18] As well, some adjuvant procedures can be performed to decrease the dosage inflicted on specific organs. One group, for example, uses lead shielding of the patient's thyroid during neurointerventional procedures to decrease the amount of thyroid radiation.[13]

Deterministic effects, by definition, vary depending on the dose of radiation exposure in any given procedure. It follows therefore that providing the expected dosage of radiation for the procedure proposed may help inform risk. The more complex or longer a procedure is predicted to be increases the amount of radiation. Table II outlines the effective dose expected or reported in various common vascular studies. In one report of endovascular aneurysm repair (EVAR), which included a small cohort of branched grafts and patients with iliac pathology, Weerakkody et al[25] noted that 29% of patients received doses that exceeded the threshold of 2 Gy for potential skin damage in a given procedure. The maximum estimated entrance skin dose during EVAR was 8.78 Gy. Despite this, no erythema or radiation-induced skin injury was found in the patients who were monitored.[25]

The stochastic effects of radiation dose are more challenging to quantify. One recent publication estimated the lifetime attributable risk of death from cancer from exposure to a single abdominal CT scan at different ages.[27] This report demonstrates the much higher risk for patients who are younger at the time of the first CT scan (Fig).

Informed consent for patients undergoing interventional radiologic procedures should include a full discussion about the use of radiation and the various stochastic and deterministic effects that may result from such exposure. Intrinsic in this discussion is the rationale for using radiation-based modalities of treatment rather than conventional surgical techniques. Patients may be provided with information pamphlets that further reinforce this discussion. For those who undergo complex endovascular aneurysm repairs as part of a clinical trial, the consent form for the investigational study should include the discussion about radiation exposure that occurs perioperatively.

Patient follow-up. The ICRP recommends that all patients with estimated skin doses >3 Gy should have follow-up within 10 to 14 days of exposure.[10] The appearance of skin changes and other deterministic effects can occur at variable times after exposure, as reported in Table III.[28]

A protocol for follow-up to inspect for radiation-induced skin changes to ensure that patients are routinely assessed for the deterministic effects of radiation exposure is suggested. Where possible, one should attempt to ensure that the radiation dose in therapeutic procedures is recorded in the medical record so that the appropriate deterministic effect screening can be performed. When radiation exposure has exceeded recommended dosages, primary care physicians should also be informed so that a protocol of follow-up using complete blood count, as well as physical examination for erythema or depilation, can be implemented.

CONCLUSIONS

A number of factors affect the potential injuries both patients and physicians can experience from radiation exposure. It is important that vascular surgeons and endovascular specialists performing procedures involving such exposure understand these factors and the methods for reducing exposure risks. It is also imperative that patients be informed of potential risks, particularly in complex procedures and in medical conditions where repeated radiologic procedures are required.

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