Radiation-Related Injuries and Their Management: An Update

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Abstract

Ionizing radiation (in the form of X-rays) is used for the majority of procedures in interventional radiology. This review article aimed at promoting safer use of this tool through a better understanding of radiation dose and radiation effects, and by providing guidance for setting up a quality assurance program. To this end, the authors describe different radiation descriptive quantities and their individual strengths and challenges, as well as the biologic effects of ionizing radiation, including patient-related effects such as tissue reactions (previously known as deterministic effects) and stochastic effects. In this article, the clinical presentation, immediate management, and clinical follow-up of these injuries are also discussed. Tissue reactions are important primarily from the patients' perspective, whereas stochastic effects are most relevant for pediatric patients and from an occupational viewpoint. The factors affecting the likelihood of skin reaction (the most common tissue reaction) are described, and how this condition should be managed is discussed. Setting up a robust quality assurance program around radiation dose is imperative for effective monitoring and reduction of radiation exposure to patients and operators. Recommendations for the pre-, peri-, and postprocedure periods are given, including recommendations for follow-up of high-dose cases. Special conditions such as pregnancy and radiation recall are also discussed.

Keywords
- radiation dose
- interventional radiology
- quality assurance
- occupational radiation exposure

Objectives: Upon completion of this article, the reader will be able to identify the biological effects of radiation (skin reactions in particular), the different measures of radiation dose, and how to set up a quality assurance program for minimizing radiation dose from FGIs.

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Radiation Dose Overview

Radiation is ubiquitous in its various forms throughout the environment (e.g., microwaves, radio waves, light, and heat) without causing significant hazard. However, ionizing radiation, which includes X-rays, presents a significant potential for detrimental biological effects. Ionizing radiation damages cellular DNA either directly, resulting in the ionization of a DNA molecule, or indirectly, from chemical reactions involving radiation-generated free radicals.[1] In theory, damage to even a single cell could result in mutated DNA with retained

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Table 1 Radiation quantities with their associated units and definitions

Radiation quantity	SI, traditional unit	Definition
Exposure (X)	Coulomb/kg (C/kg), roentgen (R)	The amount of charge liberated per unit mass of air
Absorbed dose (D)	Gray (Gy), radiation absorbed dose (rad)	The amount of energy absorbed per unit mass of the absorbing medium
Equivalent dose (H_T)	Sievert (Sv), roentgen equivalent man (rem)	The absorbed dose equivalent, accounting for the type of radiation: absorbed dose multiplied by a radiation weighting factor (W_R), accounting for differences in biologic effect per unit of absorbed dose. For photons and electrons, W_R is 1
Effective dose (H_E)	Sievert (Sv), roentgen equivalent man (rem)	A calculated quantity used to express and compare risk, where W_T is the assigned tissue weighting factor representing the relative radiation sensitivity of that tissue. Current W_T values can be found in ICRP[3] Report 103
Air kerma	Gray (Gy)	The kinetic energy released in air; at photon energies used for diagnostic imaging, this quantity is very close to the absorbed dose in air
Air kerma at the interventional reference plane ($K_{a,r}$)	Gray (Gy)	The air kerma determined at the interventional reference plane, generally defined as 15 cm toward the X-ray tube from the isocenter of the fluoroscope c-arm gantry. This is the quantity displayed on most modern fluoroscopes
Peak skin dose ($D_{skin,max}$)	Gray (Gy)	The highest absorbed dose to the skin

mitotic capability, potentially leading to stochastic effects such as carcinogenesis. More extensive damage leading to large-scale cellular death may result in a reduction of tissue integrity or function, termed "tissue reactions" (formerly referred to as "deterministic effects"). Tissue reactions are defined by a threshold dose below which a reaction would not occur and above which a reaction increases in severity proportional to the increased dose. Stochastic effects, conversely, are based on the statistical probability of inducing an effect; they do not have an associated threshold, and increasing dose increases the probability of inducing an effect but not the severity.[2]

Numerous descriptive quantities are used to define radiation energy deposition and radiation dose (►**Table 1**).[3] The primary quantity of interest for patients undergoing a fluoroscopic-guided intervention (FGI) is the peak skin dose ($D_{skin,max}$), which best represents the potential for a tissue reaction. Unfortunately, $D_{skin,max}$ is not reported by most modern fluoroscopic systems; the air kerma at the interventional reference plane ($K_{a,r}$) is generally provided instead and is commonly used as a surrogate for $D_{skin,max}$. However, $K_{a,r}$ can differ significantly from $D_{skin,max}$ for several reasons. Most fluoroscopic systems measure $K_{a,r}$ using an ionization chamber mounted on top of the X-ray collimator, and the International Electrotechnical Commission (IEC)-allowable tolerance for this device is ± 35%. An additional uncertainty of approximately ± 35% arises from factors such as variations in the geometric orientation of the fluoroscope in relation to the patient, attenuation by the procedure table and pad, the tissue backscatter factor, and differences in the X-ray absorption characteristics of air and soft tissue, all of which affect $D_{skin,max}$ but are not accounted for in $K_{a,r}$.[4] ►**Fig. 1** illustrates the effect of variations in the geometric orientation of the fluoroscope with respect to the two-dimensional dose distribution at the skin entrance for a fenestrated and branched endovascular repair. The film darkness correlates to radiation dose at each location and demonstrates the contribution of the discrete X-ray fields to the $D_{skin,max}$. $K_{a,r}$ is not capable of differentiating among discrete X-ray fields; it is simply the sum of all exposures irrespective of their contribution to $D_{skin,max}$. Although $K_{a,r}$ is often used by clinicians as a surrogate for patient dose, it

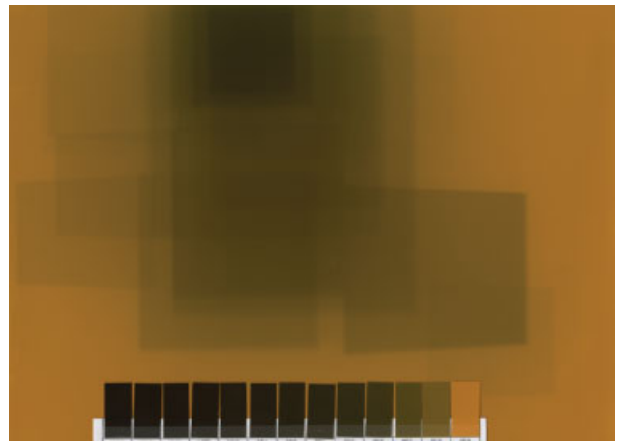

Fig. 1 Radiochromic film (14 inches × 17 inches) from a fenestrated and branched endovascular repair showing the two-dimensional radiation dose distribution. Film darkness is correlative to increased radiation dose.

must be understood that this value likely differs substantially from the $D_{skin,max}$.

Tissue Reactions

For kilovoltage energy X-ray beams, such as those used for fluoroscopic imaging, the maximum radiation dose resides at the skin surface, making the skin the primary organ of concern for tissue reactions.[5] Although uncommon in diagnostic and interventional radiology, tissue reactions are generally well understood, with a known temporal and symptomatic progression based on radiation dose (►**Table 2**).[6] The X-ray beam skin entrance location is the primary area of concern; for most interventional radiology procedures, this area will reside on the patient's back. These reactions can affect dermal (including hair), subcutaneous, and muscle tissues, and have also been documented in cranial bones from neurointerventional procedures.[7]

The radiation doses and latency periods identified in ►**Table 2** are approximate and do not represent rigid thresholds. Numerous factors may exacerbate these reactions, including patient-specific factors such as smoking, obesity, the presence of overlapping skin folds, poor nutrition, and preexisting skin degradation in the irradiated area; genetic disorders such as ataxia telangiectasia, Gorlin syndrome, Fanconi anemia, Bloom syndrome, xeroderma pigmentosum, familial polyposis, Gardner syndrome, hereditary malignant melanoma, and dysplastic nevus syndrome; diseases such as scleroderma, systemic lupus erythematosus, rheumatoid arthritis, hyperthyroidism, and diabetes mellitus; and the concurrent use of certain drugs such as doxorubicin, tamoxifen, methotrexate, bleomycin, 5-fluorouracil, and actinomycin D.[8–10] The location of the irradiated skin is also important, with locations in order of decreasing radiation sensitivity being anterior surface of the neck, flexor surfaces of the extremities, the trunk, the back, extensor surfaces of the extremities, the scalp, and the palms of the hands and soles of the feet.[11] Patients with light-colored hair and skin are most sensitive to radiation. All of the aforementioned potential factors complicate the prediction of a reaction based solely on an estimated $D_{skin,max}$.

Radiation recall, a tissue reaction precipitated by the presence of a catalyst drug potentially years after radiation exposure, has also been documented from an FGI irradiation,[12] indicating the need for review of patient medications should a suspected radiation-induced tissue reaction present in greater severity than expected or outside of the typical time course for expression.

Management of Radiation-Related Injuries: Patient Quality Assurance

The International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and various professional organizations have all recommended establishing a system to monitor and record patient dose, or a dose surrogate, from FGIs as part of a comprehensive quality assurance program.[13,14] Because of the wide variability in tissue reactions and their time course for expression, a patient monitoring system should be conservative in its approach to setting thresholds for required monitoring or follow-up. The NCRP published a report entitled "Radiation Dose Management for Fluoroscopically Guided Interventional Medical Procedures" in 2011[13]; in addition to being a comprehensive review of radiation physics and biology pertaining to FGI procedures, this report establishes recommendations for a quality assurance program and is the basis for the recommendations that follow in this article.

Preprocedural Quality Assurance

Preprocedural quality assurance for FGIs should include a risk–benefit analysis and informed consent process that take

Table 2 Skin reaction progression with dose

Single irradiation peak skin dose (Gy)	Predicted National Cancer Institute skin reaction grade[a]	Approximate reaction latency			
		Prompt (hours to 2 wk)	Early (2–8 wk)	Mid (6–40 wk)	Late (>40 wk)
<2	Not applicable	No effect predicted			
2–5	1	Mild pruritus, transient erythema		No effect predicted	
5–10	1–2	Intense pruritus, transient erythema	Dyspigmentation (hyper or hypo, potentially permanent), edema, epilation, erythema		Dermal atrophy, telangiectasia
10–15	2–3		Dyspigmentation (hyper or hypo, potentially permanent), desquamation (wet or dry), edema, epilation, erythema, necrosis, ulceration		
>15	3–4 (surgical repair likely required)	Desquamation (wet or dry), edema, pruritus, transient erythema			Dermal atrophy, necrosis, telangiectasia, ulceration

[a]Based on the National Cancer Institute Common Terminology Criteria for Adverse Events.[16]

into account a patient's radiation history, specifically identifying previous FGIs or radiation therapy in or around the anatomy to be imaged. If high radiation doses are anticipated, staged interventions may be appropriate, with delays between stages offering the potential for repair of radiation damage. van den Aardweg et al[15] studied fractionated X-ray radiation exposures on pig skin and found that ~1 day of separation between exposures allowed for significant repair of sublethal cellular damage, offering a "repair capacity" between 20 and 25% for both early and late epidermal responses. For absorbed doses below 15 Gy, an additional delay of up to 14 days offered no appreciable benefit; however, a delay beyond 14 days and up to 56 days provided increased repair and repopulation, culminating in nearly complete recovery of the basal skin layer.[6] Although these results are believed to translate to human response, caution should be used in rigidly applying these results clinically because they were obtained from pig skin irradiation using X-rays of greater energy than those employed in fluoroscopic imaging. When multiple FGIs over the same anatomic region are necessary and clinical circumstances allow, a delay of ~8 weeks between procedures may provide substantial benefit in reducing the potential severity of a radiation-induced tissue reaction[6]; if an 8-week delay is not feasible, even a 24-hour period between irradiations could provide considerable benefit.[15]

Pregnancy status must be determined before any nonemergency interventional procedure is performed. If an FGI is necessary in a pregnant patient, a qualified medical physicist (QMP) should be engaged to assist with procedure planning and monitoring. Careful consideration should be given to the vascular access location; depending on the type of intervention, a nonfemoral approach may eliminate exposure of the fetus to the primary X-ray beam. A lead apron or skirt may be positioned beneath the patient or wrapped around her pelvis as long as it would not potentially enter the primary X-ray field. All potential radiation dose-saving techniques must be considered, including minimizing the fluoroscopic pulse and acquisition frame rates, replacing acquisitions with saved fluoroscopic loops, replacing spot radiographs with saved last-image holds, minimizing the X-ray field by collimation, and using the other procedure-related dose-reducing techniques described below.

Periprocedural Quality Assurance

Proficient operation of the fluoroscope is vital to ensure optimum radiation dose and image quality. Ideally, procedures would be performed at the lowest possible image quality (and dose) necessary to achieve the clinical goal. This optimal image quality will vary depending on clinical needs as well as operator preferences and ability. All procedures should start with an appropriate imaging protocol designed for the clinical task and optimized for the necessary spatial resolution, image contrast, and patient dose. For a system with multiple fluoroscopic dose settings, the lowest dose setting should be selected by default, requiring operator action to increase the dose if better image quality is necessary.

Radiation dose to the patient and operator are significantly affected by the geometric orientation of the fluoroscope. The image receptor should be positioned as close to the patient as possible, with the patient situated as far from the X-ray focal spot as possible. One exception to this orientation is for isocentric imaging, which requires a specific anatomic structure to remain in the center of the image as the fluoroscope gantry angle is changed (e.g., c-arm cone beam computed tomogram [CT]). Short clinicians may consider the use of operating room platforms or similar devices to allow the procedure table to be elevated, thus reducing the skin entrance dose to the patient. During a procedure, clinicians must use caution when attempting to angulate the fluoroscope for the sole purpose of reducing the $D_{skin,max}$ by spreading out the dose. This technique requires sufficient angle variation (30 degrees or more in some cases) and judicious collimation to avoid an unintentional increase in the $D_{skin,max}$.[16]

All staff present for FGIs must be engaged to identify opportunities for radiation dose reduction, as patient dose reduction proportionately reduces the occupational radiation dose to all personnel in the imaging suite.

Postprocedural Quality Assurance

The patient dose or dose surrogate (e.g., $K_{a,r}$) should be documented in the patient's medical record after each FGI.[13,14] Dose or dose surrogate thresholds should be established to trigger patient education and follow-up. The NCRP refers to these thresholds as "substantial radiation dose levels" (SRDLs) and recommends an SRDL for $D_{skin,max}$ of 3 Gy (if available) or $K_{a,r}$ of 5 Gy. These SRDLs are intended solely to trigger a monitoring process and do not define an expectation for a tissue reaction. At SRDL threshold values, tissue reactions will be unlikely without additional confounding factors; however, it is important to structure a monitoring program with the goal of identifying all substantial tissue reactions. Conservatively, for patients undergoing multiple FGIs over similar anatomic regions, radiation dose should be summed over a 6-month period.[5] This is also within the Joint Commission's recommended time period of 6 to 12 months for determining a cumulative skin dose exceeding 15 Gy from fluoroscopic irradiation, constituting a sentinel event.

After procedures in which SRDLs are exceeded, the patient and primary caregiver(s) (including clinical caregivers) should be advised that a substantial radiation dose was delivered and should then be educated about the potential adverse effects, their general time course for expression, and whom to contact should a tissue reaction develop. A member of the clinical team should contact the patient for follow-up at ~4 weeks after the procedure; if a tissue reaction is present or cannot be ruled out, the patient should be examined by a member of the clinical team and a QMP. All follow-up results should be documented in the patient's medical record. Guidelines for patient follow-up after radiation exposure are outlined in ►**Table 3**.[6]

When a tissue reaction occurs, it should be graded according to the National Cancer Institute's gradation scale for skin reactions (see ►**Table 4**).[17] For a pictorial representation of the different reaction grades, see the appendix of the article

Table 3 General advice to be provided to patients and treating physicians

$D_{skin,max}$ range (Gy)	Advice to patient and treating physicians
0–2	No need to inform patient, because there should be no visible effects; if patient reports skin changes, then treat in response to the signs and symptoms
2–5	Advise patient that erythema may be observed but should fade with time; advise patient to contact the physician performing the intervention if skin changes cause physical discomfort
5–10	Advise patient to perform self-examination or ask a partner to examine for skin effects from ~2 to 10 weeks after the procedure; tell patient where skin effects would most likely occur; if skin erythema and itching occur, patient should call radiologist's office; skin reactions are often treated conservatively; might advise patient to be examined by dermatologist or other treating physician and to inform treating physician that injury may be due to radiation; radiologist should also provide that physician with medical details of where the radiation-related skin effects are likely to occur
10–15	Medical follow-up is appropriate; advice is same as that for previous range but dermatologist or other treating physician should also be advised that skin effects may be prolonged due to radiation dose and that prophylactic treatment for infection and monitoring of wound progression may be required; pain could become a concern if doses were in the higher end of this range
>15	Medical follow-up is essential, with the nature and frequency of follow-up depending on estimated radiation dose; advice is same as that for previous two ranges, but treating physician should be advised that the wound could progress to ulceration or necrosis

Source: Adapted with permission from Balter et al.[6]

Table 4 Grading of radiation dermatitis[a] by NCI CTCAE[16]

Grade			
1	2	3	4
Faint erythema or dry desquamation	Moderate to brisk erythema; patchy moist desquamation, mostly confined to skin folds and creases; moderate edema	Moist desquamation in areas other than skin folds and creases; bleeding induced by minor trauma or abrasion	Life-threatening consequences; skin necrosis or ulceration of full thickness dermis; spontaneous bleeding from involved site; skin graft indicated

[a]A finding of cutaneous inflammatory reaction occurring as a result of exposure to biologically effective levels of ionizing radiation.

by Balter et al.[6] For a patient presenting with a tissue reaction, periodic documentation of the reaction severity and progression, preferably with photographs, should be added to the electronic medical record until the reaction is fully resolved. All procedures resulting in a tissue reaction should be reviewed by a clinical quality committee to ensure that all reasonable dose-saving measures were taken and to determine whether medical necessity justified the radiation dose delivered.[13] A QMP should calculate an estimated $D_{skin,max}$, providing an indication of the potential reaction severity. For an estimated $D_{skin,max}$ below 5 Gy, a reaction requiring intervention is unlikely; symptomatic treatment and avoidance of further skin aggravation are all the measures that are generally necessary.[6] For an estimated $D_{skin,max}$ between 5 and 10 Gy, an appreciable reaction should be anticipated; in these cases, a dermatology consult is encouraged for reaction monitoring and management. For an estimated $D_{skin,max}$ greater than 10 Gy, a reaction requiring surgical intervention is possible; for these patients, dermatology evaluation and monitoring should be initiated as soon as possible. For serious reactions, a multidisciplinary approach is essential, with representation of specialists in wound care, dermatology, and plastic surgery who have experience in managing radiation reactions. A comprehensive symptom management guideline regarding radiation dermatitis was created by the BC Cancer Agency and may be consulted for an extensive review.[18]

Stochastic Effects

Patient-Related Effects

Although FGIs may result in appreciable effective doses, in adults the stochastic risk is generally less than other procedure-related risks or the underlying risk from the clinical condition requiring the intervention.[19–21] For pediatric interventions, effective dose must be considered more closely, as the stochastic risk for this population is higher than for adults (up to a factor of ~3 for newborns).[21] The linear-no-threshold (LNT) model is the currently accepted model for determining the relationship between effective dose and cancer risk.[22] As the name implies, the LNT model contends that there is a linear relationship between cancer risk and effective dose, and that there is no dose threshold below which cancer risk is not increased. However, the concept of effective dose and its use within the LNT model is controversial even within the medical and health physics communities

who established the quantity.[23] At high doses of radiation (above ~100 mSv), the LNT model is widely accepted. However, at low doses (including most exposures from diagnostic and interventional radiology procedures), there is tremendous uncertainty.[24] For purposes of radiation protection or regulatory compliance, this uncertainty can be reasonably overlooked, as conservatism is warranted and nonindividual radiation doses are considered. However, it is inappropriate to apply the LNT model and effective dose estimates to individuals for the purpose of calculating cancer risk to an individual from a specific radiation exposure.[3]

Occupational-Related Effects

Stochastic effects are the primary concern for clinicians involved in FGI procedures; it is highly unlikely for someone to reach a threshold dose for a tissue reaction resulting from an occupational radiation exposure in a medical environment. Monitoring of occupational radiation dose should be required for all persons involved in FGIs and ensured by the fluoroscope operator before the start of each procedure. For physicians routinely performing FGIs, the NCRP recommends using a 2-dosimeter monitoring system, allowing for a more accurate whole body dose estimate; a single dosimeter approach substantially overestimates this dose, depending on where the dosimeter is located.[25]

Occupational doses should be kept as low as reasonably achievable. To accomplish this, facilities must provide adequate radiation protection tools, and individuals must appropriately and consistently use them. All clinicians required to be at the patient's side during FGIs must wear protective apparel, which should include a lead-equivalent apron (preferably a vest and wraparound skirt as opposed to a single-sided apron), thyroid collar, and glasses. Lead-equivalent glasses should have temples sufficiently broad to attenuate radiation incident from the side, because the operator will generally be viewing the monitors and not the patient during radiation production. In addition, lead-acrylic pull-down shields and tableside lead-equivalent drapes should be available and routinely employed. These shields typically provide 95% or greater attenuation of incident scattered radiation; this is in addition to the protection offered by the lead-equivalent apparel.

Conclusion

The common use of FGIs over recent decades has greatly affected patient care, as these procedures are generally less invasive with lower complication rates and comparable or better efficacy rates as compared with their surgical alternatives.[20] However, high doses of radiation can pose a significant risk to the patient and operator. Engaging the patient and caregivers along the continuum of care when there is a potential for radiation-induced reactions provides transparency and monitoring for early detection and management of radiation-induced tissue reactions. When clinical and technical staff members work together, radiation dose to all parties can be controlled and minimized through optimization of imaging techniques and through the routine use of available safety equipment.

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