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Fundamentals of Medical Radiation Safety: Focus on Reducing Short-Term and Long-Term Harmful Exposures

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Additional information is available at the end of the chapter

Abstract

This chapter provides an overview of key topics in the area of radiation safety. Three clinical vignettes will serve to frame the review of the literature around both diagnostic radiation exposure and the risk of radioisotope contamination. Advancement in medical technology is rarely innocuous, and the use of radiation as both means to diagnose and treat certain conditions is not an exception. It is very important for clinicians to review the basics of harmful medical radiation exposure since, although seldom encountered, treatment, and outcomes are time sensitive. The advent of newer technology and the widespread availability of equipment will only serve to increase the prevalence of potentially harmful medical radiation exposure. Moreover, this chapter aims to explore current multidisciplinary endeavors to provide safe and efficient use of radiation in medicine. Solely relying on the medical profession for development of safeguards against harmful medical radiation exposure would be an impossible task. This is why it is crucial for professionals such as health physicists, radiation safety enforcement officers, and policy-makers at the state, national, and international level to establish consensus guidelines aimed toward safe, reliable utilization of radiation in medicine. Part of this interdisciplinary approach needs to focus on accurate education of patients. A thorough assessment of acute radiation syndrome, including diagnosis, treatment, and prognostic indicators is also part of this chapter. Furthermore, principles of screening for, and protection from, radiation contamination are outlined. Finally, areas for further research are identified throughout the chapter. The discussion takes into account both US-based and International research and practice guidelines.

Keywords: diagnostic radiation exposure, patient safety, radiation exposure, radiation safety, radioisotope contamination, safety protocols

1. Introduction

Because of its low incidence, the risk of patient exposure to ionizing radiation is often under-estimated—and underappreciated—as a patient safety (PS) threat across various healthcare settings. Consequently, the Joint Commission mandates that hospitals prepare for managing radiation-related risks in terms of protecting patients from unnecessary exposure, limiting any associated potential damage, monitoring the types and extent of radiation, and maintaining proficiency in decontamination procedures in cases of direct radioactive isotope contact [1, 2]. In terms of everyday healthcare facility functioning, there is a dual focus to ensure that radiation safety standards are met: (a) avoidance of unnecessary exposure including improper dosing and (b) assurance that radioactive material will be properly handled and disposed [2].

Regardless of the details or the mode of delivery, the intent of the treating team should always be the reduction in both short- and long-term radiation exposures [3]. It has been recommended by different organizations and authors that radiation exposure reduction (RER) efforts encompass both pre-procedural and procedural phases of treatment [4, 5]. The use of radiation for diagnostic or therapeutic indications (RDTI) has clear benefits when appropriately directed and supervised. However, serious errors, prolonged or repeated exposures, and lack of supervision can be associated with significant adverse consequences, including the risk of acute radiation sickness, malignancy, and death [6–10]. **Table 1** [top section] lists the

Side effect	Frequency	Minimum exposure amount (Rads)
Hyperpigmentation/erythema	>50%	50–200
Mild fatigue	>50%	50–200
Mild myelosuppression	>50%	50–200
Skin desquamation	<10%	100
Mild nausea/vomiting/diarrhea	<10%	100–400
Intractable vomiting/diarrhea	90%	>400
Comparison of alternative units of measure		**Conversion factor**
1 Rad		0.01 Joule/kg; 0.01 Gray; 0.01 Sv
1 Millirad		0.00001 Joule/kg; 0.00001 Gray; 0.00001 Sv
1 Milligray; 1 Centigray; 1 Decigray; 1 Dekagray		0.1; 1; 10; 1000 Rads, etc. (respectively)
1 Coulomb/kg		3876 Roentgen; 3875 Parker; 3875 Rep
1 Millicoulomb/kg		3.876 Roentgen*
1 Microcoulomb/kg		0.003876 Roentgen*
1 Tissue Roentgen		1 Roentgen

kg = kilogram; Sv = Sievert; * = same applies for Parker and Rep units.

Table 1. Approximate incidence of adverse effect at different radiation exposures measured in Rads.

approximate incidence of adverse effects at various levels of radiation exposure (measured in Rads). In addition, comparative descriptions of alternative radiation units of measure are provided for the reader in the lower section of **Table 1**. The latter measure is intended to reduce the confusion often encountered due to multiple naming conventions in this area of science.

An important distinction must be made between radiation exposure and radioactive contamination. Radiation exposure refers to a person receiving energy in the form of waves or particles from an external source or from internal contamination [9, 10]. To prevent harm to the patient, the duration of exposure is carefully controlled. To prevent harm to the radiology technician, distance and shielding from source are employed [11, 12]. In contrast, a contaminated person has radioactive material on (or inside) the body secondary to ingestion, inhalation or deposition on the body surface. Thus, contamination can be classified as internal or external. Most patients exposed to radiation are not contaminated [13]. Radiation can be measured in SI unit Gray (Gy), which represents the absorption of one joule of radiation energy per kilogram of matter. In order to reflect the degree of radioactive contamination in human tissue, the unit of Sievert (Sv) us usually employed. The following clinical vignettes will illustrate both radiation exposure (#1) and contamination (#2 and #3). For the purposes of our chapter, the reader should be familiar with the three general types of radiation, including the associated energetic characteristics and shielding capacity (**Table 2**). In addition, various levels of radiation exposure (measured in millisieverts) including the typical associated contextual settings are shown in **Figure 1**.

1.1. Clinical vignette #1

Over a period of months, numerous patients who underwent computed tomography (CT) perfusion scans of the brain at different hospitals across a wide geographic area reported vague complaints of oddly shaped patterns of unexpected hair loss. Reportedly, the mostly band-like areas of alopecia appeared within 1–2 weeks following each patient's CT study. Some patients began complaining of new onset memory loss and/or difficulty keeping balance while walking. Given the unusual pattern of clinical signs and symptoms, as well as the isolated nature of occurrences, it took months before the connection was made between CT perfusion scans and what turned out to be significant radiation overdoses. When the true scope of the problem became evident, hundreds of patients were identified as having received approximately eight times the expected levels of radiation. It appeared that the root cause for the above occurrences may be faulty programming of CT scanner devices. A nationwide statement of caution was issued by the FDA, urging hospitals across the US to

Type of radiation	Penetrating energy	Penetrating capacity in human body	Shielding capacity
Alpha (α)	Low	Epidermis	Dissipates in air
Beta (β)	Intermediate	Soft tissue	Sheet of paper
Gamma (γ)	High	Bones and organs	Lead

Table 2. Types of ionizing radiation, with corresponding levels of penetration and preferred shielding characteristics.
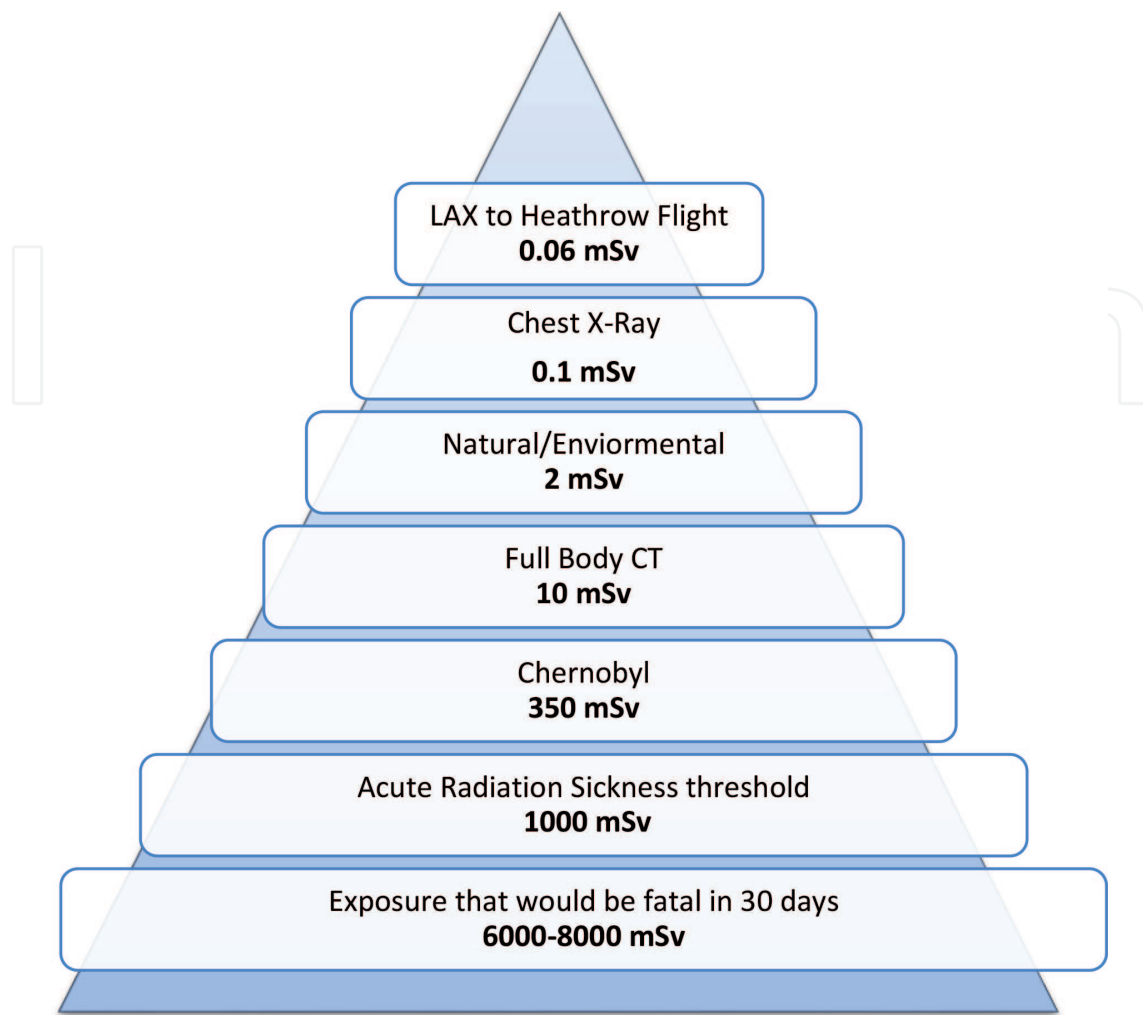
Figure 1. Different levels of radiation exposure, measured in millisieverts (mSv) and the associated biological manifestations.

review institutional CT scan logs to check radiation dosage levels and data regarding applicable adherence to established dosing protocols [14, 15]. In response to the above events, the first state law in the US aimed at protecting patients from excessive radiation exposure during CT scans was signed into law by Gov. Arnold Schwarzenegger of California [16]. In addition to providing an accreditation mandate for CT scanners, the bill also requires that radiation dose be recorded on the scanned image in a patient's medical record, and that radiation overdoses be reported to patients, treating physicians, and the state Department of Public Health [16].

1.2. Clinical vignette #2

In 1987, improperly abandoned hospital radiation equipment in Goiania, Brazil, led to the contamination of a large number of people. During the post-incident review, it was discovered that an unused irradiation machine was left behind when a privately owned healthcare facility moved. The device was subsequently stolen by a group of young men who sold it to a scrap metal dealer. During the disassembly of the medical equipment, a broken capsule

of the highly radioactive cesium-137 was accidentally smashed, along with its lead enclosure, liberating "shiny bluish dust which glowed in the dark" [17]. Unaware of the danger, numerous individuals associated with the scrap metal yard owner came into contact with the radioactive powder. The most seriously affected victims developed alopecia, cutaneous burns, vomiting and diarrhea. The governmental response was slow at first, due mainly to the lack of recognition of the magnitude and the urgency of the situation. Experts from the Soviet Union and the US were involved in the subsequent management and containment of the radioactive risk. The incident was thought to be the most serious of its kind at the time, with 240 documented cases of contamination, 20 hospitalizations, and 4 fatalities [17, 18].

1.3. Clinical vignette #3

In 1992, an unexpected discovery of radioactive waste was made by a regional disposal company in Indiana, Pennsylvania [9, 19]. Subsequent investigation by the US National Regulatory Commission (NRC) found that in November of 1992, a local clinic in Indiana, Pennsylvania treated a patient with high-dose brachytherapy using an iridium-192 radioactive source [20]. It was determined that the treatment was not completed due to equipment-related issues. Unknown to the operators, the source wire became fractured and remained in the patient. Investigators discovered that the required radiation survey at the end of the treatment was not performed. The patient was discharged to a nursing home and died 5 days later. Unaware of the danger, nursing home staff removed the source-containing catheter and disposed of it as biohazardous waste [9]. The source was identified during routine radiation surveillance by the waste disposal company. In addition to being a contributor to the index patient's death, more than 90 individuals may have been exposed to the radioactive material, with doses ranging from <0.05 to >2.55 rem [20].

2. The magnitude of the "silent" problem

Difficult to identify at the time of the initial exposure, radiation injury tends to present in a delayed fashion. Radiation injury also tends to be low on a typical differential diagnosis list as most cases tend to involve unintentional (and unrecognized) exposure. As demonstrated by our three vignettes, the uncommon occurrence of harmful medical radiation exposure (HMRE) can originate as a result of various types of PS error; both of omission and of commission [21]. In addition, radiation-related PS issues can result from lack of adequate oversight at both institutional level (e.g., absent safety procedures) and governmental level (e.g., lack of applicable laws, regulations, or enforcement) [9, 22, 23].

Complexities associated with HMRE prompted an important discussion regarding the nature and the content of the informed consent process, specifically as it relates to medical radiation exposure [24]. The true gravity of such considerations is exemplified by the known association between cumulative radiation exposure and the incremental risk of malignancy following repeated CT imaging episodes [25]. Moreover, compared to the adult population, the overall risk is significantly greater for pediatric patients [26].

3. Biological manifestations of HMRE

Two broad categories of clinical (e.g., biologic) effects of radiation, specific to the contexts of radiation therapy or accidental isotope exposure, include deterministic injuries and stochastic injuries. Deterministic injuries manifest as radiation-induced escalation of normal physiologic apoptosis resulting in increased death of essential cells with resultant tissue and organ dysfunction [27]. These types of injuries occur when large numbers of cells become damaged and, as a result, die immediately or shortly after irradiation [28]. Dermatoligic post-exposure injury can range from "local erythema" to "skin necrosis" [28]. Estimation of dosage is measured in the units of Gy, with 0–2 Gy associated with no biological effects; 2–5 Gy causing transient erythema (<2 weeks), followed by epilation (2–8 weeks) and recovery (6–52 weeks); 5–10 Gy associated with prolonged erythema (up to 8 weeks), epilation (2–8 weeks), and recovery (6–52 weeks); 10–15 Gy exposure causes transient erythema (<2 weeks), dry/moist desquamation (2–8 weeks), followed by permanent epilation (6–52 weeks) and finally atrophy (>40 weeks); and >15 Gy being associated with acute ulceration (<2 weeks), moist desquamation (2–8 weeks), dermal necrosis (6–52 weeks), and eventual surgery (>40 weeks) [28]. **Table 3** outlines the above exposure levels in a systematized fashion.

Stochastic effects manifest as cellular carcinogenesis and result from radiation induced mutations in genetic material of cells including germ cells [27]. For stochastic injuries, post-radiation damage becomes the key determinant of clinically apparent, usually long-term manifestation [28]. Such effects also depend on the type/activity of the isotope involved. More specifically, these kinds of injuries have a linear nonthreshold dose that may lead to radiation-induced malignancy and/or heritable genetic defects [28]. Estimation of dosage from radiologic studies utilizes the units of Sieverts (Sv), with procedures such as dual-isotope SPECT (24 mSv) and CT angiography (19 mSv), carrying the highest effective radiation doses [28]. Of note, victims of the Chernobyl disaster were exposed to a maximum radioactivity of 300–450 mSv/h within a 15 km radius. The individuals that had suffered from radiation are suspected to have received a minimum of 0.8–2 Gy (80–200 Rad) dose [28].

Radiation dose (Gy)	Possible adverse reaction	Timeline
0–2	No effect	
2–5	Transient erythema	<2 weeks
5–10	Prolonged erythema	<8 weeks
10–15	Dry/moist desquamation leading to permanent epilation	2–8 weeks → 6–52 weeks
>15	Acute ulceration leading to desquamation and dermal necrosis	<2 weeks → 6–52 weeks

Table 3. Post-exposure deterministic injury shown with radiation dose in Gray units and the typical timeline associated with the appearance of adverse effects.

4. Regulatory mechanisms and safety enforcement

The first line of ensuring safety is the presence of organizational policies and procedures pertaining to HMRE as well as the handling of radioisotope-containing medical materials, both at the departmental and institutional levels [29–31]. In addition to applicable policies and procedures that are harmonized to prevailing laws and regulations, organizations also employ radiation safety experts in the role of Radiation Safety Officer (or functional equivalent thereof) to ensure the maintenance of appropriate legal and procedural compliance [31–33]. Any HMRE events that are deemed reportable to appropriate local, regional, or national authorities are handled by the Radiation Safety Officer. In addition, employees who work around radiation equipment and/or interact with medical radioisotopes must wear radiation monitoring badges that help quantify levels of healthcare worker exposure [34, 35]. Some general considerations of how appropriate policies and procedures can help protect the well-being of both patients and healthcare workers include [7, 32, 36–38]:

- In diagnostic radiography, the use of hardwired "safety prompts" helps facilitate double-checking of the expected radiation dosage; also, it is important to ensure the presence of appropriate warning lights, such as "X-ray in progress" and sufficiently labeled facilities with caution signs

- Ensuring that the delivery process of therapeutic radiation is appropriately structured, including thorough planning, simulated application, and the presence of built-in cross-checks (e.g., two or more experts sign-off on the final therapeutic plan, including the physician, the physicist, and a dosimetrist)

- Monitoring of cumulative monthly radiation exposure and limiting further exposure for those employees who exceeded established thresholds

- Protocolized monitoring of medical waste for the presence of radioactivity, both at the site of origin (e.g., the hospital) and at the destination (e.g., landfill)

In the European Union and associated countries, the Euratom Treaty recommends that a patient examination and clinical justification are provided before a referral is made to a radiologist or a nuclear medicine expert. Moreover, nonionizing radiation is preferred whenever it will provide comparable information to that obtained by means of ionizing radiation [39]. For example, an ultrasound or magnetic resonance imaging (MRI) may provide the same desired information as a CT, without the need for ionizing radiation [40]. Additional safety enforcement strategies include: safety checklists to verify the patient and study being performed; radiation dose customization utilizing the patient's weight, age, medical history, and intended body segment to be scanned/imaged; and decision support systems which provide ordering physicians an opportunity to answer questions regarding their patients and consider alternatives to ionizing diagnostics [40].

The US Food and Drug Administration (FDA) has partnered with other organizations to promote education and communication regarding radiation safety to patients and medical professionals

[41]. Among their resources, the FDA collaborated with the National Council on Radiation Protection and Measurement to communicate the risk of radiation exposure with patients, particularly imaging involving young children [41, 42]. The FDA advocates for patient and healthcare provider awareness via the Image Wisely and Image Gently radiation risk campaigns, as well as with the International Atomic Energy Agency's "Radiation Protection of Patients" website [41, 43, 44]. The FDA has also advocated for patient and healthcare provider tools to reduce radiation exposure. One particular innovative safety tool is the "Patient Medical Imaging Record Card", which was developed by the FDA in collaboration with Image Wisely [41, 43]. The card can be used to track patient imaging studies by date, type, and location to prevent unnecessary repeat ionizing radiation exposures [41]. Looking toward the future, this card would ideally be integrated into the patient's electronic health record and stored in a nationally accessible database for healthcare providers, such as the Federal Data service Hub, which is established by the Affordable Care Act and backed by the Health and Human Services department [45].

The US Nuclear Regulatory Commission was established with The Energy Reorganization Act of 1974 to license and regulate the civilian use of radioactive materials to protect public health and safety and the environment. It is in charge of overseeing nuclear reactors, security, and materials as well as radioactive waste. The commission sets rules and licensing, enforces those rules, evaluates facilities, and provides support and logistics for incident response. Some aspects of management and regulation of certain radioactive materials have been granted to Agreement States [46].

5. Radiation injury

Although most individuals exposed to radiation contamination are not symptomatic, the consequences of such exposures tend to result in long-term sequelae [47–50]. Providers should be aware of signs and symptoms of radiation injury so that such occurrences can be readily recognized, contained, and victims treated promptly [51, 52]. As demonstrated in our *Clinical Vignette #1*, acute HMRE tends to have organ-specific, regional anatomic manifestations (e.g., pneumonitis, lung fibrosis, gastric ulceration, and radiation proctitis) [52–54]. Systemic manifestations (e.g., acute radiation syndrome) are extremely rare in the healthcare setting and usually involve direct exposures of patients, workers, or otherwise unsuspecting individuals, to the radioactive isotope material, as outlined in our *clinical vignette #2* [18, 55] and *clinical vignette #3* [9, 19, 20].

Acute radiation syndrome (ARaS), unlike radiation injury, is a systemic entity that occurs very rarely in the healthcare setting. It usually involves some form of equipment failure, radioactive isotope release, criminal activity/theft, or inappropriate disposal of equipment or isotope(s) [9, 18–20, 55]. Because ARaS may be the only overt "manifestation" of a major radioactive breach, it is critical that it is promptly recognized, and that it leads to a thorough investigation into associated events. Symptoms of ARaS evolve over time in distinct phases. The duration of each phase and the time of its onset will be approximately inversely proportional to the dose [56]. An initial prodromal phase, with symptoms such as nausea, vomiting, weakness, and fatigue, typically develops within hours to days after exposure of the

Syndrome	Hematopoietic	Gastrointestinal	Cardiovascular/neurovascular
Dose	>0.3–0.7 Gy	>6–10 Gy	>20–50 Gy
Prodromal stage (minutes—2 days)	Anorexia, nausea/vomiting	Anorexia, severe nausea, vomiting, cramps, and diarrhea	Extreme nervousness and confusion, severe nausea, vomiting, watery diarrhea, loss of consciousness and burning sensation of the skin
Latent stage	Patient appears well for 1–6 weeks	Patient appears and feels well for less than a week	Patient may return to partial functionality (often lasts less than several hours)
Manifest illness stage	Anorexia, fever, and malaise Drop in all blood cell counts Primary cause of death is infection and hemorrhage Most deaths within a few months Survival rate is inversely proportional to dose	Malaise, anorexia, severe diarrhea, fever, dehydration, and electrolyte imbalance Death occurs within 2 weeks after exposure	Watery diarrhea, convulsions, and coma Onset occurs 5–6 hours after exposure Death occurs within 3 days of exposure
Recovery	Full recovery for large percentage of patients from a few weeks to 2 years after exposure Death may occur in some individuals at 1.2 Gy The $LD_{50/60}$ is 2.5 to 5 Gy	The LD_{100} is about 10 Gy	No recovery expected

Table 4. Acute radiation syndrome: most common manifestations [13].

whole body to radiation exceeding 0.7 Gray (Gy). ARaS manifests most acutely and severely in the hematopoietic, gastrointestinal, and cardiovascular/neurovascular systems [27, 57]. Radiation-induced gastrointestinal manifestations of ARaS manifest as nausea, vomiting, and bloody diarrhea. Severe dermatological injury with burns, desquamation, epilation, and ulceration can occur after significant radiation exposure even in the absence of ARaS [58], as exemplified by our *clinical vignette #1*. The above manifestations are summarized in **Table 4**.

6. Protection from and screening for radiation contamination

The general principles of protection from radiation injury depend upon four factors: distance, time, shielding, and removal or containment of contamination [27]. When caring for potential radiation contaminated patients, healthcare personnel must minimize the duration of exposure to a source, maximize the distance from source, and establish effective shielding from the source. Identification of the presence of radioactive contamination on or within a patient mandates early removal/containment in order to forestall further damage and contamination [27]. In cases similar to the Goiania incident, hand-held Geiger counters must be utilized in order to focus on accurately identifying anatomic areas of contamination unique

to each individual [1]. Substantial exposure of emergency responders and clinicians caring for potentially heavily contaminated patients may occur. Emergency medical services and clinicians must use caution and adhere to strict precautions for managing hazardous materials to prevent inadvertent contamination of themselves and others [27]. Personnel should wear radiation dosimeters, sealed in clear, airtight plastic bags, and worn outside the clothing to allow rapid assessment and early detection of contamination. Workers and work areas should undergo repeated surveillance with radiation detectors at appropriate intervals [1, 27].

7. Laboratory evaluation of acute radiation injury

In cases of more significant exposure, ARaS manifests initially through the hematopoietic system as blood marrow tissues are highly radiosensitive [27]. Of all the components of hematopoiesis, circulating lymphocytes have the most radiosensitive cell lines and provides a useful laboratory tool to screen for the severity of the radiation sickness early in observation (**Figure 2**) [56]. After whole body exposure above 0.5 Gy, the rapid fall in lymphocyte number starts within hours, and the lymphocyte depletion is proportional to the dose between 1 and 10 Gy [56]. GM-CSF may be helpful for the recovery of the bone marrow function after clinically significant radiation exposure [57]. Lymphocyte depletion kinetics serves as the single best estimator of radiation exposure and clinical outcome [27]. A decrease in absolute lymphocyte levels may be observed at whole-body doses as low as 100 mSv, but clinically significant response may not be seen below 1–2 Sv. Depending on the absorbed dose, such changes can begin within hours of exposure, so it is recommended that an immediate complete blood count with differential is performed as a baseline and then every 6–12 hours thereafter for 2–3 days [27]. An elevated serum amylase provides a supplementary piece of information that may also be an early sign of serious radiation exposure involving the head and neck. The results of this test are nonspecific; however, and they may also reflect alcohol intake, a stress response, trauma
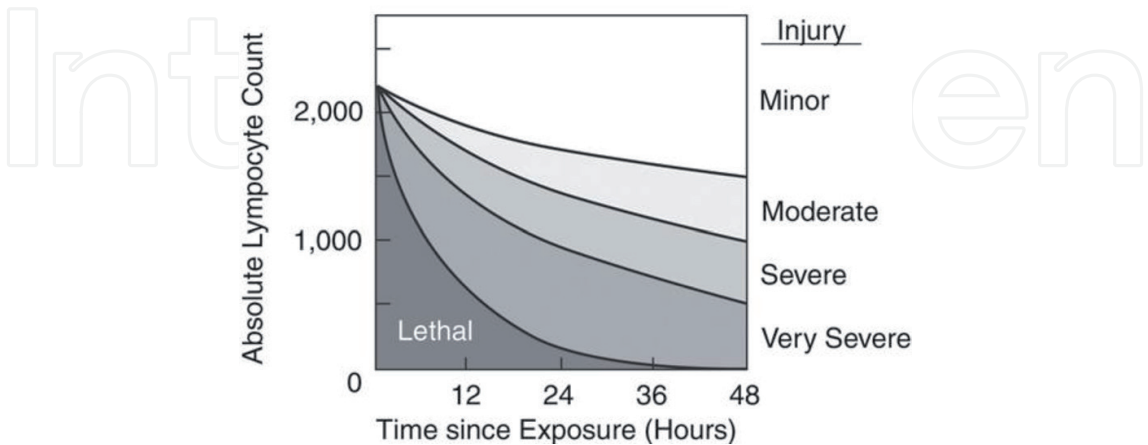

Figure 2. Time-dependent lymphocyte depletion kinetics following either severe or moderate radiation exposures. As early as 6–12 hours following exposure, there may be some indication of the severity of the exposure [35].

to the face or abdomen, or other factors [27]. In addition, the presence of nausea and vomiting within several (usually around 4) hours of exposure may also be diagnostically helpful.

8. Measuring severity of radiation dose

Similar to other toxicological phenomena, determining the potential harm of radiation exposure mandates consideration of three factors: dose of radiation exposure, tissue or surface area exposed, and duration of exposure. Whole body radiation exposure to 4 or 5 Sv (or Gy) imparts potentially lethal effects, while an extremity can tolerate several times that exposure [27]. General measures of radiation exposure (e.g., fluoroscopy time) have low utility and accuracy [28]. At this juncture, it is important to introduce the concept of KERMA, or "Kinetic Energy Released in Matter", which is a measure of energy delivered (or dose) [28]. Air-KERMA is the KERMA measured in air (e.g., low scatter environment) [28]. More useful methods of determining radiation administered include: (a) total air-KERMA (exposure) at pre-specified reference point, (b) air-KERMA area product, and (c) peak skin dose or the maximum dose received by any local area of patient skin [28, 59]. See **Figures 3–5** for further information.
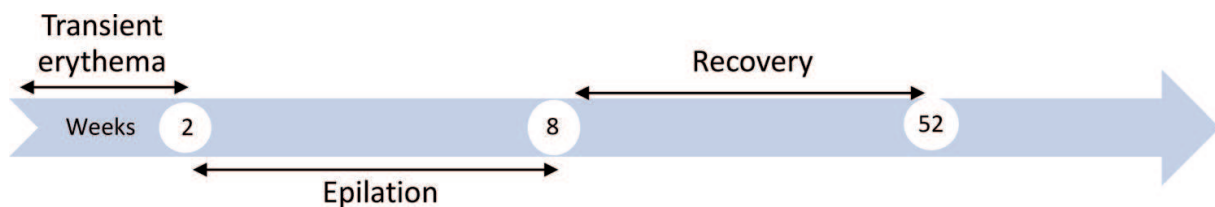
Figure 3. Timeline for post exposure injury for dosage of 2–5 Gy.
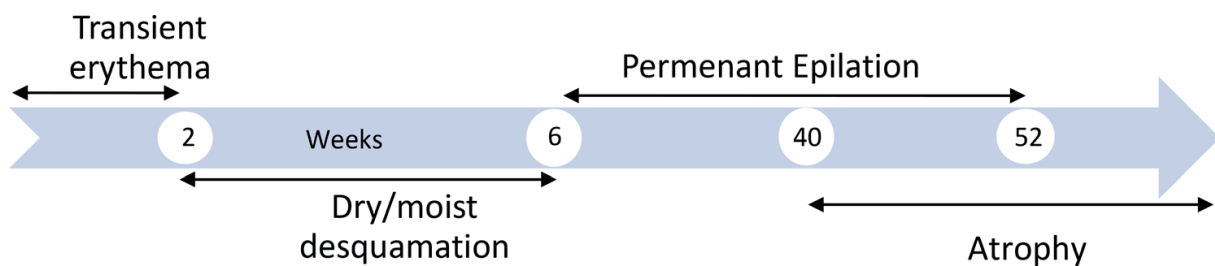
Figure 4. Timeline for post exposure injury for dosage of 10–15 Gy.
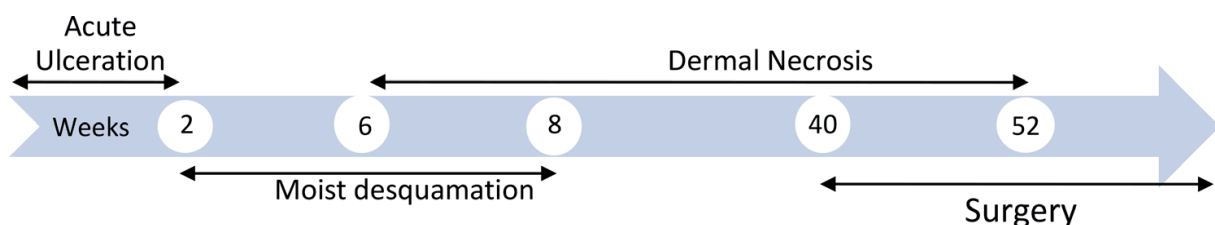
Figure 5. Timeline for post exposure injury for dosage >15 Gy.

9. Patient exposure to radiation

A point of concern among care providers and parents is the risk of radiation exposure from medical imaging, especially in the pediatric population. Epidemiologic studies have shown that *in utero* exposure to radiation is associated with higher incidence of pediatric cancers, but data related to rates of pediatric and adult cancers are relatively scarce [60]. In recent years, CT scanning has become the favored imaging modality in many clinical scenarios and is likely to see even further increases in use going forward [61–63]. As such, CT utilization in pediatrics has increased markedly over the last 20 years. Over 85 million CT scans are performed annually in the United States, with 5–11% of these performed on children [64]. Before we embark on further discussion, important dose-related information in the context of diagnostic testing is provided in **Table 5**.

A typical CT scan of the head of a child carries an average dose of 2–2.5 millisieverts (mSv) of radiation. CT imaging of the chest and abdomen carries doses averaging 3–4 and 5–6 mSv, respectively. The actual dose administered differs from the more nebulous effective dose, as other factors make the amount of radiation exposure more meaningful in children than adults. The effective radiation doses received by children are about 50% higher than those received by adults for similar imaging studies due to smaller body sizes and radiation attenuation [66, 67]. Up to an age of 10, children are approximately three times more sensitive to radiation than adults, which is why longer life expectancy coupled with organ systems that are still developing disproportionately increases the relative burden of pediatric radiation exposure [67–69].

Several studies have attempted to answer questions regarding specific childhood cancer risks associated with radiation exposure. Two studies showed increased incidence of pediatric leukemia in children with medical radiation exposure; however, these studies used retrospective questionnaire data and their result as inconsistent with older data [70, 71]. Certain genetic phenotypes might make some children more sensitive to the effects of radiation and risk of acute lymphocytic leukemia [72]. Very limited data exist on CT-attributable risk of

Relative radiation level	Adult effective dose estimate range (mSv)	Pediatric effective dose estimate range (mSv)	Example examinations
O	0	0	Ultrasound; MRI
☢	<0.1	<0.03	Chest X-ray; hand X-rays
☢☢	0.1–1	0.03–0.3	Pelvis X-ray; mammography
☢☢☢	1–10	0.3–3	Abdomen CT; nuclear medicine bone scan
☢☢☢☢	10–30	3–10	Abdomen CT with and without contrast; whole body PET
☢☢☢☢☢	30–100	10–30	CTA chest abdomen pelvis with contrast; transjugular intrahepatic portosystemic shunt placement

Table 5. Relative radiation level designations along with associated effective adult and pediatric doses, as well as imaging examinations that correspond to said levels [65].

solid tumors in children. There is weak evidence regarding the association between radiation exposure and such occurrences (e.g., pediatric astrocytoma and Ewing's sarcoma), but this connection is in no way definitive [60].

Data regarding the lifetime risk of cancers appear to be more robust. A large retrospective cohort study reviewed >175,000 patients from the NHS registry in England [26]. The authors noted a positive association between dose of radiation from CT imaging and leukemia and brain tumors. They found relative risk of leukemia to be 3.18 in patients who received more than 30 mSv of cumulative radiation. Similarly, they found an increased relative risk of brain cancer to be 2.82 in pediatric patients who received cumulative dosing of 50 mSv or more [26]. The caveat to these data, however, is that these are rare cancers to begin with, thus the absolute relative risk increase is very small. Although the relative risk of brain cancer may nearly triple with significant cumulative radiation exposure, the absolute risk is still exceedingly small. Based on robust statistical models, for every 100,000 skull/brain CT scans in 5-year-old children, eight brain/central nervous system cancers and four cases of leukemia would result [73]. The same study estimates that 100,000 chest CT scans would lead to an excess of 31 thyroid cancers, 55 breast malignancies, and 1 leukemia case [73]. Consequently, the lifetime risk of cancers, although small, should be discussed with parents of children undergoing CT scanning. Although these studies are largely safe in children, unnecessary exposure to radiation should still be avoided, and diagnostic tests not utilizing ionizing radiation should be used whenever possible. The medical necessity of imaging should be weighed against the relatively small risk of harm when determining the appropriateness of these studies. Again, the greatest risk of cancer appears to exist when children are exposed to cumulative doses of radiation greater than 30–50 mSv.

10. Pregnancy and reproductive health considerations

According to the American College of Radiology, no single diagnostic X-ray study or procedure results in radiation exposure sufficient to threaten the well-being of the pregnant patient, the developing embryo, or the fetus [74]. In fact, diagnostic radiation exposures during pregnancy may be safer than the frequent concerns over *in utero* radiation exposure suggest [75]. Moreover, the utilization of diagnostic radiological imaging may entail more benefit than risk in the evaluation of certain maternal injuries or illnesses [76]. As much attention should focus on limiting diagnostic radiation exposure of the gravid woman's breast tissue, to prevent carcinogenesis, as on limiting radiation exposure of the fetus [77, 78]. In the setting of pregnancy, radiation exposure should be limited to 1 mGy during the first trimester, with teratogenicity risk being elevated at 5 mGy [79]. In addition, iodine-containing contrast media may lead to hypothyroidism in the fetus, an additional consideration when performing radiographic studies utilizing contrast material [79]. Counseling of the patient by the referring clinician and by the radiologist is essential in providing informed consent as the benefits and risks of procedures can be opaque and the decision may impart lasting consequences [80]. Impacting 5–7% of all pregnancies, trauma represents an important cause of nonobstetric maternal morbidity and mortality [81]. Consequently, the risk-benefit equation regarding diagnostic imaging in this particular setting is somewhat different, with the mantra that the best way to ensure fetal wellbeing is to aggressively treat the mother [82].

11. Radiation exposure as low as reasonably achievable (ALARA)

Literature suggesting that accrual of cumulative radiation exposures from diagnostic radiological studies, such as CT scans or fluoroscopy, over the course of patients' lifetimes puts them at risk for the potential carcinogenic risks of radiation [83, 84]. One example here comes from the area of endovascular interventional procedures. Since the introduction of endovascular therapy in the late 1980s, there has been incredible growth in this group of procedural modalities. In fact, endovascular procedures have increased approximately 400% over the past decade [85]. The applicability and medical advancements of this form of therapy have revolutionized treatment of our patients. However, there has been an associated cost, including substantial risk of ionizing radiation exposure [86]. Some of the pioneers of endovascular therapy have succumbed to the deleterious consequence of ionizing radiation [87]. Radiation safety practices have made tremendous advances since the discovery of Roentgen's X-rays over 120 years ago. Early practitioners were focused on patient outcomes and providing minimally invasive methods to treat complex disease processes. These sacrifices of early practitioners led to our awareness and knowledge that now allows us to perform truly remarkable treatments to benefit our patients. A number of very practical steps can be taken to reduce radiation exposure to patients, operators, and staff [88, 89]. Awareness itself can be an effective first step in reducing exposure. Once awareness of the problem exists, we can then work to educate and enact training and methodology to achieve maximal safety to our patients and ourselves. However, despite the available data, there remains a significant safety deficit. In 2014, a survey of US vascular surgery trainees found 45% had no formal radiation safety training, 74% were unaware of the radiation safety policy for pregnant females, 48% did not know their radiation safety officer's contact information, and 43% were unaware of the acceptable yearly levels of radiation exposure [90]. However, an important observation was that the trainees who felt their attendings were applying ALARA techniques were much more likely to do so themselves. Therefore, it is incumbent on those of us providing training to the next generation of caregivers to set an example of excellence and expect the same from our trainees. Only by expecting excellence can we hope to achieve superior safety for our patients and ourselves.

Advocates for radiation safety recommend exposing patients, especially children, to as little radiation as possible. This is embodied within the concept of "as low as reasonably achievable" (ALARA) in the context of radiation exposure [84]. As such, ALARA addresses the role for healthcare providers, particularly those caring for children, in reducing exposure to radiation while maintaining the reliability of the diagnostic radiology modality [91]. Multiple methods can be used to achieve ALARA including: adjusting the amount of radiation in the diagnostic study based on patient weight, considering alternative modalities such as sonography or magnetic resonance imaging, enhancing shielding with thyroid or breast shields, focusing on the suspicious area with focused or limited view diagnostic imaging, and discouraging repeat CT scan studies [91]. In one example, although noninvasive multi-slice cardiac-computed tomography angiography (CCTA) can accurately screen for coronary ischemia, its widespread utilization has generated concern because of potential diagnostic radiation exposure. Utilization of a radiation dose reduction program in concert with limiting the image acquisition window for CCTA has demonstrated marked reduction, more than 50%, in estimated radiation doses in a statewide

registry without impairment of image quality [83]. In another example, appendicitis represents the most common disease process resulting in increased CT scan utilization in children over the last two decades. Clinical practice guidelines advocating for "abdominal sonography first" for the evaluation of appendicitis have demonstrated comparable diagnostic accuracy to CT scan imaging, while reducing CT scan utilization and thus radiation exposure [91]. The Pediatric Emergency Care Applied Research Network collaborative development of a clinical decision guideline for pediatric head trauma is another example of research helping to reduce the medical radiation footprint by reliably identifying patients at low risk for clinically important traumatic brain injuries, for whom CT can routinely be obviated [92].

12. Safety protocols

Careful adherence to existing PS protocols, including active surveillance for any signs and/or symptoms of HMRE, is among the most important considerations for facilities/departments providing diagnostic and/or therapeutic radiation services [28]. In addition to direct radiation, the formation of X-ray image is inherently associated with some degree of "scattered radiation" that is the principal source of exposure to the patient and medical staff [28]. This "scatter" increases with both intensity of the X-ray beam and the size of the exposed field [28]. Any hospital employing medical radiation needs to have an infrastructure to support protocols for every step of the way throughout the application of said radiation including patient and healthcare worker safety, proper identification and dosing, and waste management of materials in order to prevent contamination.

13. Conclusions

The power to harness ionizing radiation for medical uses has a history spanning more than a century. Although its positive impact on the modern-day prowess of the diagnostician is unquestionable, great care must be taken in order to not abuse this technology. Diagnostic imaging with ionizing radiation seems poised to be part of the medical armamentarium for the foreseeable future. Further research is required in all aspects of this field, including more efficient protocols for delivery, custom-tailoring therapy which takes into account the patients' makeup, potential short-term and long-term harmful effects, the prediction and prevention of harm and better safeguards for dosimetry not only for patients but also for healthcare workers. Greater strides must be achieved in the realm of oversight and standardization of practice, as well as a comprehensive, nonpunitive reporting system for adverse events. A multidisciplinary approach from health physicists, radiation safety personnel, and clinicians is paramount for the management of contamination events and for the safe and accurate use of both diagnostic and therapeutic medical radiation. The key for this technology going forward is for education to be widespread among all levels of healthcare, from patients and their families to healthcare providers and policy makers. Research and public health information dissemination will go hand-in-hand throughout the next century of medical radiation use.

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