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Radiation Exposure and Contamination

Ionizing radiation injures tissues variably, depending on factors such as radiation dose, rate of exposure, type of radiation, and part of the body exposed. Symptoms may be local (eg, burns) or systemic (eg, acute radiation sickness). Diagnosis is by history of exposure, symptoms and signs, and sometimes use of radiation detection equipment to localize and identify radionuclide contamination. Management focuses on associated traumatic injuries, decontamination, supportive measures, and minimizing exposure of health care workers. Patients with severe acute radiation sickness receive reverse isolation and bone marrow support. Patients internally contaminated with certain specific radionuclides may receive uptake inhibitors or chelating agents. Prognosis is initially estimated by the time between exposure and symptoms, the severity of those symptoms, and by the lymphocyte count during the initial 24 to 72 h.
Ionizing radiation is emitted by radioactive elements and by equipment such as x-ray and radiation therapy machines.

Types of radiation

Radiation includes

- High-energy electromagnetic waves (x-rays, gamma rays)
- Particles (alpha particles, beta particles, neutrons)

Alpha particles are energetic helium nuclei emitted by some radionuclides with high atomic numbers (eg, plutonium, radium, uranium); they cannot penetrate skin beyond a shallow depth (< 0.1 mm).
Beta particles are high-energy electrons that are emitted from the nuclei of unstable atoms (eg, cesium-137, iodine-131). These particles can penetrate more deeply into skin (1 to 2 cm) and cause both epithelial and subepithelial damage.
Neutrons are electrically neutral particles emitted by a few radionuclides (eg, californium-252) and produced in nuclear fission reactions (eg, in nuclear reactors); they can penetrate deeply into tissues (> 2 cm), where they collide with the nuclei of stable atoms, resulting in emission of energetic protons, alpha and beta particles, and gamma radiation.
Gamma radiation and x-rays are electromagnetic radiation (ie, photons) of very short wavelength that can penetrate deeply into tissue (many centimeters). While some photons deposit all their energy in the body, other photons of the same energy may only deposit a fraction of their energy and others may pass completely through the body without interacting.
Because of these characteristics, alpha and beta particles cause the most damage when the radioactive atoms that emit them are *within* the body (internal contamination) or, in the case of beta-emitters, directly *on* the body; only tissue in close proximity to the radionuclide is affected. Gamma rays and x-rays can cause damage distant from their source and are typically responsible for acute radiation syndromes (ARS—see Radiation Exposure and Contamination: Acute Radiation Syndromes [ARS]).
Measurement of radiation
Conventional units of measurement include the roentgen, rad, and rem. The roentgen (R) is a unit of exposure measuring the ionizing ability of x- or gamma radiation in air. The radiation absorbed dose (rad) is the amount of that radiation energy absorbed per unit of mass. Because biologic damage per rad varies with radiation type (eg, it is higher for neutrons than for x- or gamma radiation), the dose in rad is corrected by a quality factor; the resulting effective dose unit is the roentgen equivalent in man (rem). Outside the US and in the scientific literature, SI units are used, in which the rad is replaced by the gray

(Gy) and the rem by the sievert (Sv); 1 Gy= 100 rad and 1 Sv = 100 rem. The rad and rem (and hence Gy and Sv) are essentially equal (ie, the quality factor equals 1) when describing gamma or beta radiation.

Types of exposure

Radiation exposure may involve

- Contamination
- Irradiation

Radioactive contamination is the unintended contact with and retention of radioactive material, usually as a dust or liquid. Contamination may be

- External
- Internal

External contamination is that on skin or clothing, from which some can fall or be rubbed off, contaminating other people and objects. Internal contamination is unintended radioactive material within the body, which it may enter by ingestion, inhalation, or through breaks in the skin. Once in the body, radioactive material may be transported to various sites (eg, bone marrow), where it continues to emit radiation until it is removed or decays. Internal contamination is more difficult to remove. Although internal contamination with any radionuclide is possible, historically, most cases in which contamination posed a significant risk to the patient involved a relatively small number of radionuclides: hydrogen-3, cobalt-60, strontium-90, cesium-137, iodine-131, radium-226, uranium-235, uranium-238, plutonium-238, plutonium-239, polonium-210, and americium-241.

Irradiation is exposure to radiation but not radioactive material (ie, no contamination is involved). Radiation exposure can occur without the source of radiation (eg radioactive material, x-ray machine) being in contact with the person. When the source of the radiation is removed or turned off, exposure ends. Irradiation can involve the whole body, which, if the dose is high enough, can result in systemic symptoms and radiation syndromes (see Radiation Exposure and Contamination: Acute Radiation Syndromes [ARS]), or a small part of the body (eg, from radiation therapy), which can result in local effects. People do not emit radiation (ie, become radioactive) following irradiation.

Sources of exposure

Sources may be naturally occurring or man-made (see Table 1: Radiation Exposure and Contamination: Average Annual Radiation Exposure in the US).

People are constantly exposed to low levels of naturally occurring radiation called background radiation. Background radiation comes from cosmic radiation and from radioactive elements in the air, water, and earth. Cosmic radiation is concentrated at the poles by the earth's magnetic field and attenuated by the atmosphere. Thus, exposure is greater for people living at high latitudes, at high altitudes, or both and during airplane flights. Radioactive elements, particularly uranium and its radioactive progeny and potassium-40, are present in many rocks and minerals. These elements end up in various substances, including food, water, and construction materials. Radon, a radioactive gas resulting from the decay of uranium, typically accounts for about 2/3 of naturally occurring radiation dose to the US population. In the US, people receive an average effective dose of about 3 millisieverts (mSv)/yr from natural sources. However, in some parts of the world, people receive between 5 and 10 mSv/yr. The doses from natural background radiation are far too low to cause radiation injuries, although they may increase the risk of cancer.

In the US, people receive on the average about 3 mSv/yr from man-made sources, the vast majority of which involve medical imaging. Imaging exposure tends to be highest from CT scans and nuclear cardiology procedures. However, medical diagnostic procedures rarely impart doses sufficient to cause radiation injury, although they may increase the risk of cancer. Exceptions may include certain prolonged fluoroscopically guided interventional procedures (eg, endovascular reconstruction, vascular embolization, cardiac radiofrequency ablation); these procedures have caused injuries to skin and underlying tissues. Radiation therapy commonly causes injury to some normal tissues near the target

tissue.
A small portion of public exposure results from radiation accidents and fallout from nuclear weapons testing. Accidents may involve industrial irradiators, industrial radiography sources, and nuclear reactors. These accidents commonly result from failure to follow safety procedures (eg, interlocks being bypassed). Radiation injuries have also been caused by lost or stolen medical or industrial sources containing radionuclides. People seeking medical care for these injuries may be unaware that they were exposed to radiation.
Radioactive material has escaped from nuclear power plants, including the Three Mile Island plant in Pennsylvania in 1979 and at Chernobyl in Ukraine in 1986. Exposure from Three Mile Island was minimal; people living within 1.6 km of the plant received only about 0.08 mSv. However, people living in 2 villages near the Chernobyl plant received an average dose of about 300 mSv, and people at the Chernobyl plant itself received significantly higher doses. More than 30 workers and emergency responders died, and many more were injured. Low-level contamination from that accident was detected as far away as Europe, Asia, and even the US. The average cumulative exposure for the general population in various affected regions of Belarus, Russia, and Ukraine over a 20-yr period after the accident is estimated to be between 10 and 30 mSv.
Another significant radiation event was the detonation of 2 atomic bombs over Japan in August 1945, which caused about 110,000 deaths from the immediate trauma of the blast and heat. A much smaller number of deaths resulted later from radiation-induced illnesses.
While several criminal cases of intentional contamination of individuals have been reported, radiation exposure to a population through terrorist activities has not occurred but is a concern. A possible scenario involves the use of a device to contaminate an area by dispersing radioactive material (a radiation dispersal device that uses conventional explosives is referred to as a dirty bomb). Other terrorist scenarios include using a hidden radiation source to expose unsuspecting people to large doses of radiation, attacking a nuclear reactor or radioactive material storage facility, and detonating a nuclear weapon.

Pathophysiology
Ionizing radiation can damage DNA, RNA, and proteins directly, but more often the damage to these molecules is indirect, caused by highly reactive free radicals generated by radiation's interaction with intracellular water molecules. Large doses of radiation can cause cell death, and lower doses may interfere with cellular proliferation. Damage to other cellular components can result in progressive tissue hypoplasia, atrophy, and eventually fibrosis.

Average Annual Radiation Exposure in the US

Source	Effective Dose (millisieverts)
Naturally occurring sources	
Radon gas	2.00
Other terrestrial sources	0.28
Radiation from outer space	0.27
Natural internal radioactive elements	0.39

Subtotal	**3.0**
Man-made sources	
Diagnostic x-rays and nuclear medicine (for average person)	3.0
Consumer products	0.10
Fallout from weapons testing	< 0.01
Nuclear industry	< 0.01
Subtotal	**3.0**
Total annual exposure	**6.0**
Other sources of exposure (per Exposure or Procedure)	
Airline travel	0.005/h of flight
Dental x-rays	0.005
Chest x-ray	0.02
Mammography	0.4
CT, head	2
Nuclear medicine (eg, bone scan)	6
CT, body (chest, abdomen)	8–10
Barium enema	8

Factors affecting response

Biologic response to radiation varies with

- Tissue radiosensitivity
- Dose
- Duration of exposure

Cells and tissues differ in their radiosensitivity. In general, cells that are undifferentiated and those that have high mitotic rates (eg, stem cells) are particularly vulnerable to radiation. Because radiation preferentially depletes rapidly dividing stem cells over the more resistant mature cells, there is typically a latent period between radiation exposure and overt radiation injury. Injury does not manifest until a significant fraction of the mature cells die of natural senescence and, due to loss of stem cells, are not replaced.

Cellular sensitivities in approximate descending order from most to least sensitive are

- Lymphoid cells
- Germ cells
- Proliferating bone marrow cells
- Intestinal epithelial cells
- Epidermal stem cells
- Hepatic cells
- Epithelium of lung alveoli and biliary passages
- Kidney epithelial cells

- Endothelial cells (pleura and peritoneum)
- Nerve cells
- Bone cells
- Muscle and connective tissue cells

The severity of radiation injury depends on the dose and the length of time over which it is delivered. A single rapid dose is more damaging than the same dose given over weeks or months. Dose response also depends on the fraction of the body exposed. Significant illness is certain, and death is possible, after a whole-body dose > 4.5 Gy delivered over a short time interval; however, 10s of Gy can be well tolerated when delivered over a long period to a small area of tissue (eg, for cancer therapy).

Other factors can increase the sensitivity to radiation injury. Children are more susceptible to radiation injury because they have a higher rate of cellular proliferation. People who are homozygous for the ataxia-telangiectasia gene exhibit greatly increased sensitivity to radiation injury. Disorders, such as connective tissue disorders and diabetes, may increase the sensitivity to radiation injury. Chemotherapeutic agents also increase the sensitivity to radiation injury.

Cancer and teratogenicity

Genetic damage to somatic cells may result in malignant transformation, and damage to germ cells raises the possibility of transmissible genetic defects.

Ionizing radiation can cause cancer; whole-body exposure to 1 Gy increases the average adult's lifetime risk of cancer death from 25% to about 30%, a 20% relative risk increase but only a 5% absolute risk increase. The cancer risk from commonly encountered doses (ie, from background radiation and typical imaging tests) are much less (see Principles of Radiologic Imaging: Risks of Ionizing Radiation). Children are more susceptible because they have a higher number of future cell divisions and a longer life span during which cancer may manifest; a CT scan of the abdomen done in a 1-yr-old child is estimated to increase the estimated lifetime absolute risk of developing cancer by 0.18%. Radionuclides that are incorporated into specific tissues are potentially carcinogenic at those sites (eg, radioactive iodine increases risk of thyroid cancer).

The fetus is exceptionally susceptible to high-dose radiation injury. However, at doses < 100 mGy, teratogenic effects are unlikely; the fetal risk from radiation at doses from imaging tests that pregnant women might typically undergo is small compared with the overall risk of birth defects and the potential diagnostic benefit of the examination.

Damage to reproductive cells has been shown to cause birth defects in progeny of severely irradiated animals. However, hereditary effects have not been found in children of radiation-exposed humans, including survivors of the atomic bomb attacks in Japan.

Symptoms and Signs

Clinical manifestations depend on whether radiation exposure involves the whole body (acute radiation syndrome) or is limited to a small portion of the body (focal radiation injury).

Acute Radiation Syndromes [ARS]

After the whole body, or a large portion of the body, receives a high dose of radiation, several distinct syndromes may occur:

- Cerebrovascular syndrome
- GI syndrome
- Hematopoietic syndrome

These syndromes have 3 different phases:

- Prodromal phase (0 to 2 days after exposure): Lethargy and GI symptoms (nausea, anorexia, vomiting, diarrhea) are possible.

- Latent asymptomatic phase (0 to 31 days after exposure)
- Overt systemic illness phase: Illness is classified by the main organ system affected.

Which syndrome develops, its severity, and rate of progression depends on radiation dose (see Table 2:Radiation Exposure and Contamination: Effects of Whole-Body Irradiation From External Radiation or Internal Absorption). The symptoms and time course are fairly consistent for a given dose of radiation and thus can help estimate radiation exposure.

The **cerebrovascular syndrome**, the dominant manifestation of extremely high whole-body doses of radiation (> 30 Gy), is always fatal. The prodrome develops within minutes to 1 h of exposure. There is little or no latent phase. Patients develop tremors, seizures, ataxia, and cerebral edema and die within hours to 1 or 2 days.

The **GI syndrome** is the dominant manifestation after whole-body doses of about 6 to 30 Gy. Prodromal symptoms, often marked, develop within about 1 h and resolve within 2 days. During the latent period of 4 to 5 days, GI mucosal cells die. Cell death is followed by intractable nausea, vomiting, and diarrhea, which lead to severe dehydration and electrolyte imbalances, diminished plasma volume, and vascular collapse. Necrosis of intestine may also occur, predisposing to bacteremia and sepsis. Death is common. Patients receiving > 10 Gy may have cerebrovascular symptoms (suggesting a lethal dose). Survivors also have the hematopoietic syndrome.

The **hematopoietic syndrome** is the dominant manifestation after whole-body doses of about 1 to 6 Gy and consists of a generalized pancytopenia. A mild prodrome may begin after 1 to 6 h, lasting 24 to 48 h. Bone marrow stem cells are significantly depleted, but mature blood cells in circulation are largely unaffected (circulating lymphocytes are an exception, and lymphopenia may be evident within hours to days after exposure). As the cells in circulation die by senescence, they are not replaced in sufficient numbers, resulting in pancytopenia. Thus, patients remain asymptomatic during a latent period of up to 4 ½ wk after a 1-Gy dose as marrow production falls. Risk of various infections is increased as a result of the neutropenia (most prominent at 2 to 4 wk) and decreased antibody production. Petechiae and mucosal bleeding result from thrombocytopenia, which develops within 3 to 4 wk and may persist for months. Anemia develops slowly, because preexisting RBCs have a longer life span than WBCs and platelets. Survivors have an increased incidence of radiation-induced cancer, including leukemia.

Effects of Whole-Body Irradiation From External Radiation or Internal Absorption

Phase of Syndrome	Feature	Dose Range (Gy)* † 1-2	2–6	6–8	8–30	> 30
Prodrome	Incidence of nausea and vomiting	5–50%	50–100%	75–100%	90–100%	100%
	Time of onset after exposure‡	2–6 h	1–2 h	10-60 min	< 10 min	Minutes
	Duration	< 24 h	24–48 h	< 48 h	< 48 h	N/A (patients die in < 48 h)
	Severity and incidence of diarrhea	None	None to mild (< 10%)	Heavy (>10%)	Heavy (>95%)	Heavy (100%)
	Time of onset	-	3–8 h	1–3 h	< 1 h	< 1 h

	after exposure					
	Severity and incidence of headache	Slight	Mild to moderate (50%)	Moderate (80%)	Severe (80–90%)	Severe (100%)
	Time of onset after exposure	-	4–24 h	3–4 h	1–2 h	< 1 h
	Severity and incidence of fever	Afebrile	Moderate increase (10–100%)	Moderate to severe (100%)	Severe (100%)	Severe (100%)
	Time of onset after exposure	-	1–3 h	< 1 h	< 1 h	< 1 h
	CNS function	No impairment	Cognitive impairment for 6–20 h	Cognitive impairment for > 24 h	At higher doses, rapid incapacitation May have a lucid interval of several hours	Ataxia Seizures Tremor Lethargy
Latent period	No symptoms	28–31 days	7–28 days	< 7 days	None	None
Overt illness	Clinical manifestations	Mild to moderate leukopenia Fatigue Weakness	Moderate to severe leukopenia Purpura Hemorrhage Infections Epilation after 3 Gy	Severe leukopenia High fever Diarrhea Vomiting Dizziness and disorientation Hypotension Electrolyte disturbance	Nausea Vomiting Severe diarrhea High fever Electrolyte disturbance Shock	N/A (patients die in <48h)
	Dominant organ system syndrome	Hema-topoietic	Hema-topoietic	GI tract (mucosal cells)	GI tract (mucosal cells)	CNS
	Hospitalization	Outpatient observation	Recommended to necessary	Urgent	Palliative treatment (symptomatic only)	Palliative treatment (symptomatic only)
	Acute mortality without medical care	0–5%	5–100%	95–100%	100%	100%
	Acute mortality with medical care	0–5%	5–50%	50–100%	100%	100%
	Death	6–8 wk	4–6 wk	2–4 wk	2 days–2 wk	1–2 days

*1 rad = 1 cGy; 100 rad = 1 Gy
†Whole-body irradiation of up to 1 Gy is unlikely to cause any symptoms.
‡Although time to emesis is a rapid and inexpensive method for estimating radiation dose, it should be used with caution because it is imprecise and has a high-false positive rate. Additional information, such as lymphocyte counts and details of the potential for exposure, improve accuracy.
Adapted from Military Medical Operations Armed Forces Radiobiology Research Institute: *Medical Management of Radiological Casualties, ed 2*. April 2003. (Available at the Armed Forces Radiobiology Research Institute web site.)

Cutaneous radiation injury (CRI) is injury to the skin and underlying tissues from acute radiation doses as low as 3 Gy (see Table 3: Radiation Exposure and Contamination: Focal Radiation Injury*). CRI can occur with ARS or with focal radiation exposure and ranges from mild transient erythema to necrosis. Delayed effects (> 6 mo after exposure) include hyperpigmentation and hypopigmentation, progressive fibrosis, and diffuse telangiectasia. Thin atrophic skin can be easily damaged by mild mechanical trauma. Exposed skin is at increased risk of squamous cell carcinoma. In particular, the possibility of radiation exposure should be considered when patients present with a painful nonhealing skin burn without a history of thermal injury.

Focal injury

Radiation to almost any organ can produce both acute and chronic adverse effects (see Table 3: Radiation Exposure and Contamination: Focal Radiation Injury*). In most patients, these adverse effects result from radiation therapy (see Principles of Cancer Therapy: Radiation Therapy). Other common sources of exposure include inadvertent contact with unsecured food irradiators, radiotherapy equipment, x-ray diffraction equipment or other industrial or medical radiation sources capable of producing high dose rates. Also, overexposure to x-rays during medical fluoroscopy is a source of exposure and of CRI in particular. Radiation-induced sores or ulcers may take months or years to fully develop. Patients with these injuries often have severe pain.

Diagnosis

- Symptoms, severity, and symptom latency
- Serial absolute lymphocyte counts

Diagnosis is by history of exposure, symptoms and signs, and laboratory testing. The onset, time course, and severity of symptoms can help determine radiation dose and thus also help triage patients relative to their likely consequences. However, some prodromal symptoms (eg, nausea, vomiting, diarrhea, tremors) are nonspecific, and causes other than radiation should be considered. Particularly after a terrorist attack or reactor accident, when anxiety is high, many patients *without* enough exposure to cause acute radiation sickness may present with similar, nonspecific symptoms.

After acute radiation exposure, CBC with differential and calculation of absolute lymphocyte count is done and repeated 24, 48, and 72 h after exposure to estimate the initial radiation dose and prognosis (see Table 4: Radiation Exposure and Contamination: Relationship Between Absolute Lymphocyte Count in the Adult at 48 h, Radiation Dose,* and Prognosis). The relationship between dose and lymphocyte counts can be altered by physical trauma, which can shift lymphocytes from the interstitial spaces into the vasculature, raising the lymphocyte count. This stress-related increase is transient and typically resolves within 24 to 48 h after the physical insult. CBC is repeated weekly to monitor marrow activity and as needed based on the clinical course.

Focal Radiation Injury*

Tissue	Adverse Effects

Exposed	
Brain	See Intracranial and Spinal Tumors: Radiation Therapy and Neurotoxicity
Heart and blood vessels	Chest pain, radiation pericarditis, radiation myocarditis
Skin	Dose > 3 Gy: Epilation (within 2–3 wk of exposure) Dose > 6 Gy: Local erythema Dose 8–15 Gy: Dry desquamation (within 3–4 wk of exposure) Dose 15–20 Gy: Moist desquamation (within 3–4 wk of exposure) Dose 15–25 Gy: Blister formation (within 2–3 wk of exposure) Dose > 20 Gy: Ulceration (within 2–3 wk of exposure) Dose > 25 Gy: Necrosis (> 3 wk after exposure)
Gonads	Depressed spermatogenesis, amenorrhea, decreased libido Dose > 5–6 Gy: Sterility
Head and neck	Mucositis, odynophagia, thyroid carcinoma
Muscle and bone	Myopathy, neoplastic changes, osteosarcoma
Eyes	Dose > 2 Gy: Cataracts
Lungs	Radiation pneumonitis Dose > 30 Gy: Sometimes fatal pulmonary fibrosis
Kidneys	Decreased GFR, decreased renal tubular function High doses (after 6 mo to 1 yr latent period): Proteinuria, renal insufficiency, anemia, hypertension Cumulative dose > 20 Gy in < 5 wk: Radiation fibrosis, oliguric renal failure
Spinal cord	Dose > 50 Gy: Myelopathy
Fetus	Growth restriction, congenital malformations, in-born errors of metabolism, fetal death Dose < 0.1 Gy: No significant effect Childhood cancer risk about 6%/Gy

*Typically from radiation therapy.

Relationship Between Absolute Lymphocyte Count in the Adult at 48 h, Radiation Dose,* and Prognosis

Lowest	Radiati	Prognosis

Absolute Lymphocyte Count (Cells/mL)	on Dose (Gy)	
>1500 (normal adults)†	0.4	Excellent
1000–1499	0.5–1.9	Good
500–999	2.0–3.9	Fair
100–499	4.0–7.9	Poor
< 100	8.0	Almost always fatal

*Whole-body irradiation (approximate dose).
†Children normally have higher counts that decrease with age from a median of 4600 at 0–2 yr to 3100 at 2–6 yr, and to 2300 at 7–17 yr
Adapted from Mettler FA Jr, Voelz GL: Major radiation exposure—what to expect and how to respond. *New England Journal of Medicine*346:1554–1561, 2002.

Contamination

When contamination is suspected, the entire body should be surveyed with a thin window Geiger-Muller probe attached to a survey meter (Geiger counter) to identify the location and extent of external contamination. Additionally, to detect possible internal contamination, the nares, ears, mouth, and wounds are wiped with moistened swabs that are then tested with the counter. Urine, feces, and emesis should also be tested for radioactivity if internal contamination is suspected.

Prognosis

Without medical care, the LD50/60 (dose expected to be fatal to 50% of patients within 60 days) for whole-body radiation is about 3 Gy; 6 Gy exposure is nearly always fatal. When exposure is < 6 Gy, survival is possible and is inversely related to total dose. Time to death decreases as the dose increases. Death may occur within hours to a few days in patients with the cerebral syndrome and usually within 2 days to several weeks in patients with the GI syndrome. In patients with the hematopoietic syndrome, death may occur within 4 to 8 wk because of a supervening infection or massive hemorrhage. Patients exposed to whole-body doses < 2 Gy should fully recover within 1 mo, although long-term sequelae (eg, cancer) may occur.

With medical care, the LD50/60 is 6 Gy and occasional patients have survived exposures of up to 10 Gy. Significant comorbidities, injuries, and burns worsen prognosis.

Treatment

- Treatment of severe traumatic injuries or life-threatening medical conditions first
- Minimization of health care worker radiation exposure and contamination
- Treatment of external and internal contamination
- Sometimes specific measures for particular radionuclides
- Supportive care

Radiation exposure may be accompanied by physical injuries (eg, from burn, blast, fall); *associated trauma is more immediately life threatening than radiation exposure and must be treated expeditiously* (see Approach to the Trauma Patient: Evaluation and Treatment). Trauma resuscitation of the seriously injured takes priority over decontamination efforts and must not be delayed awaiting special radiation management equipment and personnel. Standard universal precautions, as routinely used in trauma care, adequately protect the critical care team.

Extensive, reliable information about principles of radiation injuries, including management, is available at

the US Department of Health and Human Services Radiation Event Medical Management web site http://remm.nlm.gov. This information can be downloaded to a personal computer or personal digital assistant (PDA) in case Internet connectivity is lost during a radiation incident.

Preparation

The Joint Commission mandates that all hospitals have protocols and that personnel have training to deal with patients contaminated with hazardous material, including radioactive material. Identification of radioactive contamination on patients should prompt their isolation in a designated area (if practical), decontamination, and notification of the hospital radiation safety officer, public health officials, hazardous material teams, and law enforcement agencies as appropriate to investigate the source of radioactivity. Treatment area surfaces may be covered with plastic sheeting to aid in facility decontamination; this preparation should never take precedence over provision of medical stabilization. Waste receptacles (labeled “Caution, Radioactive Material”), sample containers, and Geiger counters should be readily available. All equipment that has come into contact with the room or with the patient (including ambulance equipment) should remain isolated until lack of contamination has been verified. An exception is a mass casualty situation, during which lightly contaminated critical equipment such as helicopters, ambulances, trauma rooms, and x-ray, CT, and surgical facilities, should be quickly decontaminated to the extent possible and returned to service.

Personnel involved in treating or transporting the patient should follow standard precautions, wearing caps, masks, gowns, gloves, and shoe covers. Used gear should be placed in specially marked bags or containers. Dosimeter badges should be worn to monitor radiation exposure. Personnel may be rotated to minimize exposure, and pregnant personnel should be excluded from the treatment area.

Due to the low exposure rates anticipated from most contaminated patients, medical staff members caring for typical patients are unlikely to receive doses in excess of the occupational limit of 0.05 Gy/yr. Even in the extreme case of radiation casualties from the Chernobyl nuclear reactor accident, medical personnel who treated patients in the hospital received < 0.01 Sv. Several authoritative sources suggest that a dose of up to at least 0.5 Gy may be considered an acceptable risk for lifesaving activity.

External decontamination

Typical sequence and priorities are

- Removal of clothing and external debris
- Decontamination of wounds before intact skin
- Cleaning the most contaminated areas first
- Use of a radiation survey meter to monitor progress of decontamination
- Continuing decontamination until areas are at < 2 to 3 times background radiation levels or there is no significant reduction between decontamination efforts

Clothes are removed carefully to minimize the spread of contamination and placed in labeled containers. Clothing removal eliminates about 90% of external contamination. Foreign objects should be considered contaminated until cleared by a radiation survey meter.

Contaminated wounds are decontaminated before intact skin; they are irrigated with saline and gently scrubbed with a surgical sponge. Minimal debridement of wound edges may be done if there is residual contamination after multiple attempts at cleaning. Debridement beyond the wound margin is not required, although embedded radioactive shrapnel should be removed and placed in a lead container.

If necessary, consultation is available 24 h/day from the Department of Energy Radiation Emergency Assistance Center/ Training Site (REAC/TS) at (865) 576-1005 and www.orau.gov/reacts or the Centers for Disease Control and Prevention (CDC) at (888) 246-2675 and www.bt.cdc.gov/radiation/.

Contaminated skin and hair are washed with lukewarm water and mild detergent until radiation survey meter measurements indicate < 2 to 3 times normal background radiation levels or until successive washings do not significantly reduce contamination levels. All wounds are covered during washing to

prevent the introduction of radioactive material. Scrubbing may be firm but should not abrade the skin. Special attention is usually required for fingernails and skinfolds. Hair that remains contaminated is removed with scissors or electric clippers; shaving is avoided. Inducing sweating (eg, placing a rubber glove over a contaminated hand) may help remove residual skin contamination.
Burns are rinsed gently because scrubbing may increase injury severity; subsequent dressing changes help remove residual contamination.
Decontamination is not necessary for patients who have been irradiated by an external source and are not contaminated.

Internal decontamination
Ingested radioactive material should be removed promptly by induced vomiting or lavage if exposure is recent. Frequent mouth rinsing with saline or dilute hydrogen peroxide is indicated for oral contamination. Exposed eyes should be decontaminated by directing a stream of water or saline laterally to avoid contaminating the nasolacrimal duct.
The urgency and importance of using more specific treatment measures depend on the type and amount of the radionuclide, its chemical form and metabolic characteristics (eg, solubility, affinity for specific target organs), the route of contamination (eg, inhalation, ingestion, contaminated wounds), and the efficacy of the therapeutic method. The decision to treat internal contamination requires knowledge of the potential risks; consultation with a specialist (eg, CDC or REAC/TS) is recommended.
Current methods to remove radioactive contaminants from the body (decorporation) include

- Saturation of the target organ (eg, potassium iodide for iodine isotopes)
- Chelation at the site of entry or in body fluids followed by rapid excretion (eg, Ca or zinc diethylenetriamine penta-acetate [DTPA] for americium, californium, plutonium, and yttrium)
- Acceleration of the metabolic cycle of the radionuclide by isotope dilution, (eg, water for hydrogen-3)
- Precipitation of the radionuclide in the intestinal lumen followed by fecal excretion (eg, oral Ca or aluminum phosphate solutions for strontium-90)
- Ion exchange in the GI tract, (eg, Prussian blue for cesium-137, rubidium-82, thallium-201)

Because a serious nuclear power reactor accident that released fission products into the environment could expose large groups of people to radioiodine, decorporation using oral potassium iodide (KI) has been studied in great detail. KI is > 95% effective when given at the optimal time (shortly before or immediately after exposure) and dose. However, effectiveness diminishes significantly within several hours after exposure. KI can be given either in tablet form or as a supersaturated solution (dosage: adult, 130 mg; age 3 to 18 yr, 65 mg; age 1 to 36 mo, 32 mg; age < 1 mo, 16 mg). KI is effective only for internal contamination with radioactive iodides and has no benefit in internal contamination with other radioactive elements. Most other drugs used for decorporation are much less effective than KI and reduce the dose to the patient only by 25 to 75%.

Specific management
Symptomatic treatment is given as needed and includes managing shock and hypoxia, relieving pain and anxiety, and giving sedatives (lorazepam 1 to 2 mg IV prn) to control seizures, antiemetics (metoclopramide 10 to 20 mg IV q 4 to 6 h; prochlorperazine 5 to 10 mg IV q 4 to 6 h; ondansetron 4 to 8 mg IV q 8 to 12 h) to control vomiting, and antidiarrheal agents (kaolin/pectin 30 to 60 mL po with each loose stool; loperamide 4 mg po initially, then 2 mg po with each loose stool) for diarrhea.
There is no specific treatment for the cerebrovascular syndrome. It is universally fatal; care should address patient comfort.
The GI syndrome is treated with aggressive fluid resuscitation and electrolyte replacement. Parenteral nutrition should be initiated to promote bowel rest. In febrile patients, broad-spectrum antibiotics (eg, imipenem 500 mg IV q 6 h) should be initiated immediately. Septic shock from overwhelming infection

remains the most likely cause of death.

Management of the hematopoietic syndrome is similar to that of marrow hypoplasia and pancytopenia of any cause (see Anemias Caused by Deficient Erythropoiesis: Aplastic Anemia). Blood products should be transfused to treat anemia and thrombocytopenia, and hematopoietic growth factors (granulocyte colony-stimulating factor and granulocyte macrophage colony-stimulating factor) and broad-spectrum antibiotics should be given to treat neutropenia and neutropenic fever, respectively (see Neutropenia and Lymphocytopenia: Treatment). Patients with neutropenia should also be placed in reverse isolation. With a whole-body radiation dose > 4 Gy, the probability of bone marrow recovery is poor, and hematopoietic growth factors should be given as soon as possible. Stem cell transplantation has had limited success but should be considered for exposure > 7 to 10 Gy (see Transplantation: Hematopoietic Stem Cell Transplantation).

Radiation-induced sores or ulcers that fail to heal satisfactorily may be repaired by skin grafting or other surgical procedures.

Aside from regular monitoring for signs of certain disorders (eg, ophthalmic examination for cataracts, thyroid function studies for thyroid disorders), there is no specific monitoring, screening, or treatment for specific organ injury or cancer.

Prevention

Protection from radiation exposure is accomplished by avoiding contamination with radioactive material and minimizing the duration of exposure, maximizing the distance from the source of radiation, and shielding the source. During imaging procedures that involve ionizing radiation and especially during radiation therapy for cancer, the most susceptible parts of the body (eg, female breasts, gonads, thyroid) that are not being treated or imaged are shielded by lead aprons or blocks.

Although shielding of personnel with lead aprons or commercially available transparent shields effectively reduces exposure to low-energy scattered x-rays from diagnostic imaging studies, these aprons and shields are almost useless in reducing exposure to the high-energy gamma rays produced by radionuclides that would likely be used in a terrorist incident or be released in a nuclear power plant accident. In such cases, measures that can minimize exposure include using standard precautions, undergoing decontamination efforts, and maintaining distance from contaminated patients when not actively providing care. All personnel working around radiation sources should wear dosimeter badges if they are at risk for exposures > 10% of the maximum permissible occupational dose (0.05 Sv).

Public response

After widespread high-level environmental contamination from a nuclear power plant accident or intentional release of radioactive material, exposure can be reduced either by

- Sheltering in place
- Evacuating the contaminated area

The better approach depends on many event-specific variables, including the elapsed time since initial release, whether release has stopped or is ongoing, weather conditions, availability and type of shelter, and evacuation conditions (eg, traffic, transportation availability). The public should follow the advice of local public health officials as broadcast on TV or radio as to which response option is best. If sheltering is recommended, a concrete or metal structure, particularly one below grade (eg, in a basement) is best.

Consistent and concise messages from public health officials can help reduce unnecessary panic and reduce the number of emergency department visits from people at low risk, thus keeping the emergency department from being overwhelmed. Such a communication plan should be developed prior to any event. A plan to counsel distressed people is also recommended.

People living within 16 km (10 miles) of a nuclear power plant should have ready access to KI tablets. These tablets can be obtained from local pharmacies and some public health agencies.

Preventive drugs

Radioprotective drugs, such as thiol compounds with radical scavenging properties, have been shown to reduce mortality when given before or at the time of irradiation. Amifostine is a powerful injectable

radioprotective agent in this category; it prevents xerostomia in patients undergoing radiation therapy. Although thiol compounds have good efficacy in radioprotection, these compounds cause adverse effects, such as hypotension, nausea, vomiting, and allergic reactions. Other experimental drugs and chemicals have also been shown to increase survival rates in animals if given before or during irradiation. However, these drugs can be very toxic at doses necessary to provide substantial protection, and none currently are recommended.

Last full review/revision June 2009 by Jerrold T. Bushberg, PhD, DABMP