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PEDIATRIC DISASTER PREPAREDNESS AND RESPONSE

TOPICAL COLLECTION

CHAPTER 7: NUCLEAR AND RADIOLOGICAL EVENTS

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Chapter 7:
NUCLEAR AND RADIOLOGICAL EVENTS

Although radiation is a constant exposure in daily life, a nuclear or radiological incident could pose danger to a great many people and the environment. The public may have misconceptions about what are the specific threats of harm. Medical professionals, including pediatricians, need to be knowledgeable regarding the principles and management of radiological injury, not only to provide proper diagnosis and treatment to those affected, but also to alleviate public fear and reduce potential chaos from those who are worried.

PART 1 -- SCOPE AND IMPLICATIONS

The scale of a nuclear or radiological incident can range from small to large. Nuclear incidents—whether a nuclear explosion attributable to splitting of atomic nuclei and characterized as a nuclear weapon, caused by an improvised nuclear device, or resulting from an incident at a nuclear power plant—would cause damage both at the site of an event and far away because of distribution of radioactive particles. Radioactive dispersal or exposure devices, as well as medical and industrial radiological sources, would cause additional limited damage. Health implications in any of these situations could result in radiation contamination or exposure.

Nuclear Weapons

Detonation of a weapon could occur in several contexts. The yield of a nuclear weapon is likely related to the origin of the weapon and is linked to the capacity to cause destruction. An improvised nuclear device (IND) constructed outside of a national program is anticipated to have a yield of less than 10 kilotons of TNT equivalent (1 kiloton [kT] = 1000 tons of TNT), while a stockpile weapon deployed either by a nuclear nation or after being stolen from a nuclear nation could produce a yield up to 1000 times greater.

Detonation of a nuclear weapon would cause:

- *A nuclear flash* characterized by extreme heat, light, and prompt radiation (defined as being released instantaneously)
- *A nuclear blast,* which includes an initial fireball
- *A destructive shockwave* moving outward from the explosion and resulting in extremely high winds
- *Fallout,* in which particles containing, or contaminated with, radioactive material descend to the earth's surface from a radioactive cloud

Following a nuclear detonation at elevated height, an electromagnetic pulse could produce a high-voltage surge that would not impact health but would cause local or even widespread disruption to electronic equipment.

Mechanistically in decreasing order, injuries would result from pressure, heat and light, prompt radiation, and residual radiation. Each of these has predictable effects.

- The pressure from a nuclear explosion is hundreds to millions of times more powerful than that of a conventional explosion. Injuries related to the blast are attributable to trauma with intracranial injuries, fractures, lacerations, projectile injuries, rupture of internal organs, and pulmonary hemorrhage and edema. Ruptured tympanic membranes or damaged inner ear structures may result in temporary or permanent deafness.

- The temperatures attained by nuclear explosion are much higher (tens of millions of degrees versus a few thousand) than those of a conventional explosion, causing much more of the explosive energy to be emitted as heat and light (thermal radiation). Heat can result in incineration and burn injuries and may cause fires even at considerable distances from the detonation. Light can cause flash blindness and retinal burns resulting in temporary or permanent blindness.
- Prompt radiation results quickly from the fission of nuclear material and early radioactive decay. This may contribute significantly to radiation exposure, which depends on dose, type of radiation, rate of exposure, length of exposure, and amount of the body exposed (partial or whole body).
- Residual radiation describes radiation from fallout particles and radiation activated during the initial nuclear event. Residual radiation can lead to ionizing radiation exposure and contamination. Heaviest dispersal patterns are close to the blast zone, and fallout can be carried long distances by wind. Residual radiation may persist for an extended period of time and affect animals and human living in the area.

The extent of likely radiation injury from a nuclear incident is inversely correlated with the amount of time that has passed since the event. Radiation would be highest during and immediately after an event. One hour later, radiation would be decreasing. By 24 hours after an event, radiation would have decreased significantly. Based on this timeline, avoiding radiation risks attributable to fallout would be facilitated by sheltering in place for 1 day to allow the largest radioactive particles to settle and dissipate.

Distance from ground zero could be used to estimate generalizable patterns of injury after a 10-kT IND ground explosion (see Figure 7.1). Sequelae of the explosion appears in a circular pattern, while sequelae of fallout is roughly elliptical and significantly impacted by buildings and atmospheric conditions, especially wind.

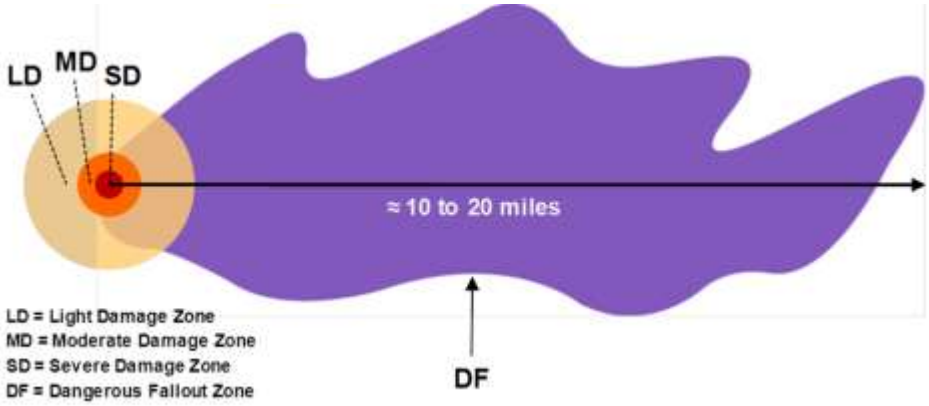

Figure 7.1. Estimate patterns of injury after a 10-kT IND ground explosion

From: Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats. Quick Reference Guide: Radiation Risk Information for Responders Following a Nuclear Detonation. December 2016. Accessed February 24, 2022.

- Severe damage would occur at 0 to 0.5 miles from ground zero. Buildings would be completely destroyed. Radiation levels would be very high for 72 hours. Bodies would be vaporized. Survivors are unlikely and most would not survive even if rescued.

- Moderate damage would occur at 0.5 to 1 mile from ground zero. Significant structural damage and early limited visibility would be expected. People would have serious injuries. Rescue efforts should be focused here, as many will only survive if rescued and treated.

- Light damage would occur at 1 to 3 miles from ground zero. Broken windows and similar structural challenges are anticipated. Most people would have non–life-threatening injuries, so they would be expected to survive without rescue or treatment. Rescue efforts will need to canvas for survivors trapped in buildings with structural damage.

- A dangerous fallout zone would extend up to 20 miles from ground zero. People should initially shelter in place, but after 24 hours, radiation levels are expected to be similar to those in the light damage zone.

- Elevated radiation area could extend up to several hundreds of miles. People should be monitored for cumulative radiation exposure and absorbed dose related to contamination.

It is important to note that the area in which a nuclear explosion occurs is likely to incur substantial physical damage, with loss of power, communication, and utilities as well as damage to electronics and communications. Medical infrastructure within the area may not be functional, requiring injured survivors to be transported to surrounding medical facilities. Survivors with chronic medical conditions (such as renal failure requiring dialysis) will also need to have their medical care transferred to functional medical facilities.

Nuclear Power Plant

The primary danger of a nuclear power plant event is release of radioactive iodine gas 131-I in the form of a plume. This plume could result in environmental deposition of radioactive material that contaminates people, livestock, food, and water. In countries where they are well regulated, nuclear power plants have significant safeguards to limit radiation injury. These include the physical structure of the facility, highly trained staff, detailed security precautions, formal incident response plans, and regular exercises.

In the United States, nuclear power plant safety is closely monitored by the Nuclear Regulatory Commission. The Nuclear Regulatory Commission has defined emergency planning zones (EPZs) adjacent to nuclear power plants to ensure a unified response. A plume exposure pathway EPZ extends around a plant at a 10 miles radius, where the risk of exposure to and inhalation of airborne radioactivity is greatest. The ingestion pathway EPZ extends around a plant at a 50-mile radius, where the risk of ingestion of contaminated food and liquid is highest.

Protective actions in case of an event could include sheltering in place or evacuation, with administration of potassium iodide (KI) when appropriate.

Radiological Dispersal and Exposure Devices

Radiological dispersal devices (RDDs) designate an attack where radioactive material is spread with the intent of doing harm, most notably psychological. A colloquially described example of an RDD is a "dirty bomb," in which a conventional explosive is used to disperse radioactive material over a targeted area.

In the case of a dirty bomb, affected people would be those closest to the site of the explosion. Most injuries would be attributable to trauma from the blast of the conventional explosive. Radiation exposure to a large group of people would be unlikely, as it would be difficult to design an RDD that could deliver a high enough radiation dose to cause clinically significant radiation exposure. Still, radioactive particles dispersed by the explosion could cause external contamination or internal contamination to limited numbers of people via inhalation, ingestion, or wounds. People who have radiation contamination attributable to an RDD would require medical evaluation and may need specific care. Long-term monitoring may be indicated to assess for delayed effects.

An attack could also be carried out with a radiological exposure device (RED) that is intended to expose passersby in a high traffic or public area to a hidden radiation source. Immediate symptoms related to acute radiation syndrome and cutaneous injury would require close proximity to the source for an extended time; however, these would likely be rare and difficult to attribute to a single attack. Hence, recognition of the radiological event and identification of the radioactive source and its location would be the greatest challenges in a situation where seemingly unconnected symptoms (hair loss, nausea/vomiting/diarrhea, low peripheral blood counts) are noted in unrelated individuals.

After an RDD or RED, mass psychosomatic symptoms may result in large numbers of people seeking care based on fears of the effects of radiation. This would strain the medical system, and it would add to the difficulty of distinguishing truly exposed people from those with gastrointestinal, dermatologic, and respiratory illnesses that are prevalent in any population at baseline.

Because the number of people with radiation injuries after an RDD or RDE would be limited, the intended effects of such attacks would be to disrupt social and economic infrastructure by causing fear. Hence, in the event of an RDD or RED, a key priority is clear communication with the community. In order to allow appropriate authorities to contain and manage the incident methodically, effective communication with the public must provide reassurance that all necessary steps are being taken to safeguard their health.

Medical and Industrial Radiological Sources

If they are used incorrectly, radioactive materials used in medical or industrial settings can cause harm from radiation exposure or contamination. Sealed sources may be used for powerful industrial radiography or Cesium-137 (an important decay product resulting from the fission of uranium and plutonium fuels) and in medical therapies. Materials that have been lost and/or stolen can result in radiation injuries.

Implications and Planning

Following a nuclear or radiological event, radiation can impact health through contamination or exposure. Radiation contamination occurs when radioactive material is on or in a person's body. Contamination can be external, as on the skin, or internal, as after inhalation or ingestion. Radiation exposure occurs when energy from radiation damages cells. Being able to distinguish between radiation contamination and radiation exposure is crucial (see Figure 7.2).

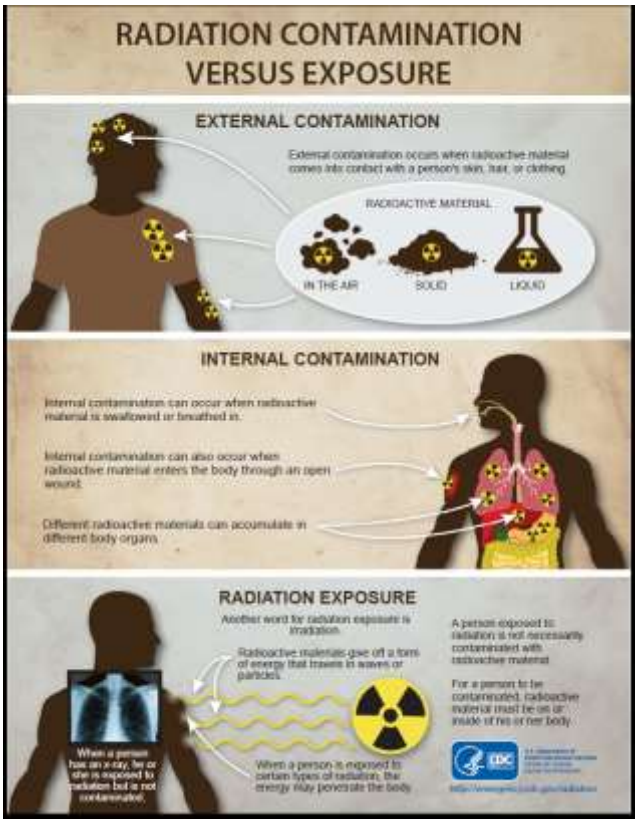

Figure 7.2. Infographic radiation contamination versus exposure

Infographic from: Centers for Disease Control and Prevention. Radiation Contamination Versus Exposure. Accessed February 24, 2022.

Public perception of the threat of a nuclear or radiological event has increased since detonation of atomic bombs in Japan that ended World War II, more recent nuclear power plant accidents, and current international events. Planning may be useful for events attributable to nuclear power facilities, RDDs, and REDs. However, responses to a large-scale event would be challenging to prepare for effectively, as detonation of a nuclear weapon would cause such destruction and crippling of infrastructure that plans would not be able to be implemented.

Planning for a smaller scale nuclear event like an IND has been undertaken thoughtfully. Although an IND has a smaller yield than a nuclear weapon, many would be killed immediately,

the injured would be numerous, and first responders attempting to help could receive significant exposure and contamination from residual radiation and radioactive fallout. Emergency management and public health expertise, including police, fire, and emergency medical service personnel, would be needed to triage patients and communicate a clear message. Treatment (see below) of patients would require subspecialty clinical expertise. Coordination of patient management would require municipal, state, and federal agencies.

The Radiation Injury Treatment Network (RITN), a cooperative effort of the National Marrow Donor Program and the American Society for Transplantation and Cellular Therapy (formerly known as the American Society for Blood and Marrow Transplantation), was formed to provide subspecialty care around a nuclear or radiological incident. A partnership of the RITN with the federal government has been formalized through a memorandum of understanding with the US Department of Health and Human Services – Assistant Secretary for Preparedness and Response, and RITN is described in federal plans. The goals of the RITN are to educate hematologists, oncologists, and stem cell transplant practitioners about their potential involvement in the response to a radiation incident and provide treatment expertise. Toward that end, the RITN developed a Concept of Operations following detonation of a 10-kT IND in which tens of thousands of people could be affected. RITN has produced standard operating procedures and treatment guidelines that can be used outside its network. These procedures address principles of acute radiation syndrome (ARS) management with recommendations for casualty triage, hospital admission order templates, and considerations for selection of candidates for HLA typing and marrow transplantation. In the case of an actual event, RITN centers will collect patient demographic, clinical, and treatment data using the standard Network Data Management Protocol (NMDP) data collection process for future research.

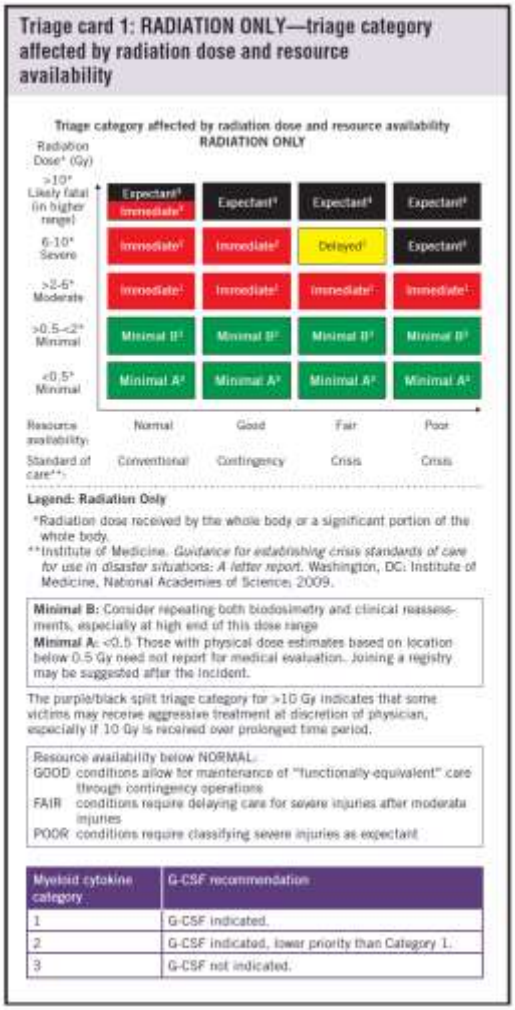

Figure 7.3. Radiation triage category affected by radiation dose and resource availability

From: REMM. Nuclear Detonation Scarce Resources Project. https://remm.hhs.gov/triagetool_intro.htm. Accessed February 24, 2022; Coleman CN, Weinstock DM, Casagrande R, et al. Triage and Treatment Tools for Use in a Scarce Resources-Crisis Standards of Care Setting After a Nuclear Detonation. *Disaster Medicine and Public Health Preparedness*. 2011;5(S1):S111-S121.

Triage and treatment of victims after an IND detonation would be challenged by limited resources and abnormal standards of care. Crisis standards of care, where normal standards of care could not be maintained, would be appropriate in this circumstance. The Scarce Resources for a Nuclear Detonation Project (https://remm.hhs.gov/triagetool_intro.htm) has made recommendations for patients requiring care that is immediate, delayed, and minimal—where minimal care means some radiation but not enough to require hospitalization early on; or expectant, where patients are treated with palliative care only (see Figure 7.3). In order to maintain ethical decision making in such a situation, treatment would be based on order of presentation, patient's medical need, and effectiveness of an intervention, while shifting the priority to those with the highest need for whom an intervention is expected to be effective.

Then, assessment for physical trauma, radiation dose, and combined injury can help to determine who should receive aggressive care.

Triage algorithms for victims of a nuclear or radiological incident can be accessed online:

- REAC/TS, Radiation Emergency Assistance Center/Training Site. https://orise.orau.gov/reacts/infographics/radiation-patient-treatment-algorithm.pdf

PART 2 – DETECTION OF RADIATION CONTAMINATION

Radiation surveillance is used to determine whether a person or the environment has been contaminated and for evaluating the effectiveness of decontamination. External contamination results when radioactive particles in solid, liquid, or gaseous form are in contact with the body. Internal contamination results when particles are internalized as a result of inhalation, ingestion, or by an impaled object or shrapnel. Decontamination is the methodical removal of external contamination.

When a nuclear or radiological event is suspected or known, then surveillance and collection of samples from people and the environment should start at the scene. Survey results should be documented before and after decontamination, by recording on an anatomic figure drawing. Sample collection must be performed with integrity, as it is crucial for both clinical and forensic evaluations. Each figure and sample must be labeled with respect to patient identification, body site, and date and time of collection. Life-threatening complications, such as the need for cardiovascular or respiratory resuscitation and management of injuries, should be treated first, prior to radiation surveillance. It is imperative that immediate life-saving procedures are not delayed to survey or decontaminate a victim.

Radiation Surveillance

Radiation detection relies on incoming radiation interacting with electrons of atoms in a detector and generating a signal that is changed into a reading or measurement. The Geiger-Mueller pancake probe is a portable instrument that can detect alpha, beta, or gamma radiation, at low levels, on people or surfaces. Electronic dosimeters have alarms that indicate preset radiation levels or cumulative exposure. Passive dosimeters may absorb radiation energy to allow later calculation of whole body exposure.

How to Perform a Survey for External Radiation Contamination

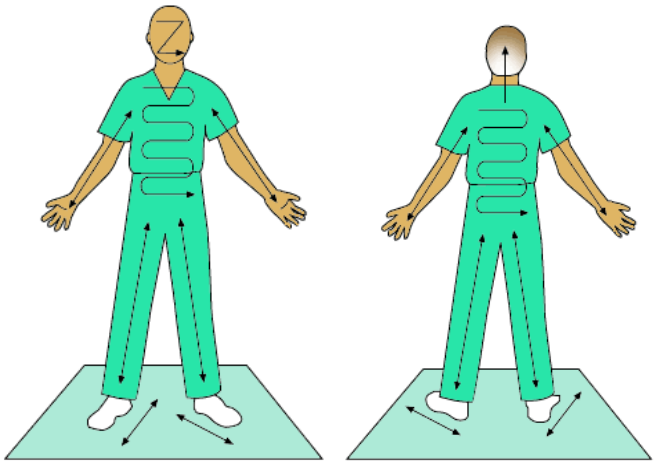

Figure 7.4. Survey for external radiation contamination

From: OSHA. *Best Practices for Protecting EMS Responders During Treatment and Transport of Victims of Hazardous Substance Releases*. OSHA 3370-11 2009. Accessed February 24, 2022.

Ideally, for each patient, the entire body should be surveyed. In brief, the survey should be conducted from head to toe as well as from side to side, with sweeping at 2 to 3 cm/sec. Counts per minute should be recorded frequently (see Figure 7.4).

In case of a large mass casualty incident, guidance exists for decontamination without radiological monitoring if there is a lack of monitoring equipment or for performing expedited survey at the most likely locations of contamination. The decision to use a "quick look" survey should be made by senior incident leaders in collaboration with specialists in radiation protection.

External Contamination and Sampling

External contamination occurs when radioactive material is in contact with the outside of a person's body or clothing. Radioactive material can be imparted primarily from radioactive fallout following a radiological incident, or secondarily from a contaminated person or the environment. External contamination can be deposited on skin and hair. The most likely areas of the body to be contaminated include hands, face, and lower legs. Fortunately, removing clothing, clearing the exposed surfaces of the body, and swabbing the nostrils and ears will remove 80% to 90% of contamination.

External contamination could occur after any nuclear or radiological incident that involves radioactive particles. External contamination increases the risk of internal contamination. Only in limited situations (external contamination with high gamma ray emitting particles or internal contamination with alpha particles) would contamination result in significant radiation exposure. With correct use of personal protective equipment (PPE) to limit secondary contamination, there is minimal risk of radiation exposure to emergency or medical personnel after most nuclear or

radiological events (except possibly after a nuclear weapon where risks and amounts of primary and secondary contamination would be higher).

If surveillance detects external radiation, then a smear or wipe sample should be collected at each site where increased signal is found. Each sample should be saved individually and labeled in a suitable specimen container for later analysis.

Internal Contamination and Sampling

Internal contamination occurs when radioactive material is taken into the airway and lungs by breathing (inhalation), into the intestines by swallowing (ingestion), or into the body through an open wound or by being impaled with radioactive shrapnel.

Evaluation of the orifices of the nose and mouth should be carried out in a timely manner, as natural clearance is completed within about 1 hour. Both nostrils should be swabbed separately and then surveyed. Of note, signal from just one nostril may suggest touching with contaminated hands. Sample collection can include saliva, sputum, vomitus if present, and urine and stool.

Wounds should be evaluated carefully, as they are more likely to be contaminated than intact skin. It is reasonable to consider that all wounds may be contaminated and that all foreign bodies may emit radiation. The wound should be uncovered for surveillance, and a swipe sample should be taken. Exudate should be collected, and embedded shrapnel should be saved for radioactive isotope identification.

PART 3 – PREVENTION AND MANAGEMENT OF RADIATION CONTAMINATION

Emergency and medical providers must use appropriate personal protective equipment (PPE) to prevent contamination of self and others and to minimize contamination of the environment. Notably, PPE does not provide protection against radiation exposure. Radiation decontamination is used to remove external contamination from victims and providers. Radiation contamination from the environment should be minimized immediately after a radiation incident and during recovery.

Personal Protective Equipment

PPE should ensure protection of the skin, eyes, nasal or oral orifices, and hands and feet. In general, PPE in the case of a radiological accident or incident involves:

- Respiratory protection to prevent internal contamination by inhalation
- Protective clothing and coverings to prevent external contamination of the skin
- Equipment for radiation surveillance

The level of PPE to be worn would be determined by the incident commander or radiation safety officer. For nuclear or radiation incidents, PPE are considered separately for first responders and first receivers.

First responders usually are at the site of an event where conditions may be hazardous. After a radiological event like an RDD, there is generally no significant risk of exposure, and therefore, a low risk of primary or secondary contamination. However, after a nuclear event like an IND, there would be some risk of residual radiation or fallout causing radiation exposure and primary

external radiation contamination. Additionally, there may be some risk of secondary radiation contamination from patients. Hence, first responders need access to PPE with the highest levels of protection. Recommended PPE includes hooded chemical-resistant clothing with optional chemical-resistant inner suit, face shield, hard hat, and chemical-resistant boots or boot covers. Recommended respiratory PPE includes a full-face air purifying respirator with a P-100 or high efficiency particulate air (HEPA) filter. Tearing of PPE should be avoided and can be prevented or managed with tape.

First receivers include clinicians and hospital staff who receive and treat exposed and contaminated victims, as well as those in roles supporting those functions. First receivers are expected to be remote from the site of an event. Therefore, they are at minimal risk of radiation exposure. However, they are at risk of secondary external contamination during care or decontamination of contaminated patients. PPE should prevent external contamination of providers and contamination of the environment, as well as later internal contamination by ingestion or inhalation. After hazardous substances have been identified and quantified and a negative-pressure respirator has been determined to be protective, then a nonpowered air-purifying respirator is recommended. In that situation, PPE is similar to that in the operating room, with water-repellent surgical gown, head cover, safety glasses/face shield/goggles, face mask, gloves, and disposable chemical-resistant outer boot covers. Double gloving with taping of the inner glove to the sleeve and frequent outer glove changes are encouraged and may additionally help to prevent spread of contamination.

Disposal of PPE should be conducted in a manner to prevent further contamination of the environment. All PPE should be collected in one area, placed in double plastic bags, and labeled as radioactive material. Later, a health physicist can assess the amount of radioactivity present to determine whether PPE should be washed, disposed of, or stored.

Decontamination

Life-saving medical care should be initiated prior to patient decontamination. Decontamination carries some risk of transferring external contamination to the health care provider; hence, appropriate PPE should be worn. Pregnant people should not provide care to patients who are externally contaminated. Radiological decontamination is not an emergency, although first aid to wounds within the first hour following contamination can significantly improve radioactive contamination removal. Decontamination should be performed by trained medical personnel or supervised by radiation safety experts.

Especially during decontamination, radiation detection for the health care provider should include a personal radiation dosimeter. Ideally, this dosimeter would provide real-time readings in addition to cumulative measurements. A finger ring dosimeter should be worn on one or both hands if débridement of radioactive shrapnel is undertaken.

Decontamination should proceed from areas of greatest contamination to least. The process should proceed as follows:

- Gross/clothing
- Embedded radioactive shrapnel
- Wounds

- Body orifices around the face
- Intact skin

Following each round of decontamination, surveillance, sampling, and documentation should be performed.

To ease triage of children after a nuclear or radiological event, questionnaire and patient flow algorithms have been developed to identify those children who are affected and to efficiently direct resources to children requiring intervention.

During radiation surveillance and contamination, children have increased risk of hypothermia and should be kept warm and dry. Further, children are anticipated to have less reserve with higher risk of dehydration from gastrointestinal (GI) tract losses with the GI subsyndrome of ARS attributable to lower intravascular volume reserve. Additionally, with respect to treatment, children may have increased risk of side effects like dehydration and electrolyte imbalance or aspiration with drugs that decrease internal contamination.

Gross external decontamination should be identifiable with a radiation detector and can be significantly reduced by removing the patient's clothing and shoes. The clothing should be removed carefully or cut, not torn, and then rolled outward away from the patient's skin such that the radioactive material is trapped in the clothing. To minimize risk of internal contamination of the patient, clothing should be moved away from the patient's face and airway; a splash shield may be applied to the patient for further protection. Contaminated clothing should be placed in a single plastic bag that is sealed and labeled.

After clothing is removed, a whole body survey should be conducted. Areas of external contamination should be noted on a body diagram that is labeled and, if possible, marked on the patient's skin. Two decontamination cycles should be conducted if detectable contamination persists. If the goal of decreased contamination to less than 2 times background is not achieved after 2 cycles of decontamination, then waterproof dressings should be applied to limit spread of contamination.

Wound decontamination starts with preparation. Any pre-existing dressing should be removed and saved. The intact skin adjacent to a wound should be decontaminated to minimize transfer into the wound and to prevent confusion with actual contamination in the wound. Waterproof drapes should be applied around and under the wound to prevent spread of contamination. Anticipated splash should be collected with absorbent pads and run-off can be directed into a receptacle like a lined waterproof can.

After preparation, the wound should be irrigated with sterile water or saline. The initial irrigation is expected to remove the bulk of contamination. When contamination is believed to be significantly reduced, the wound should be covered, the drapes removed, and a clean pad placed. Then the wound should be resurveyed. If the wound is still contaminated, then the process should be repeated until no further progress is made with reducing contamination. Multiple irrigation attempts will likely be necessary. The wound should be dried by application of absorbent material and not by rubbing with gauze, which can force contaminants into the wound. Not all contamination needs to be removed, as some remaining radiation will be incorporated

into a scab and sloughed off. After decontamination, the wound should be covered with a waterproof bandage. For a laceration, suturing should be performed after decontamination in and around the wound. For a puncture wound, simple wet débridement following standard surgical procedures should be performed. Usual infection prevention interventions should be carried out.

If contamination continues to be elevated and is not being reduced, then the wound should be explored for a radioactive foreign body. If a foreign body is visualized or suspected, distance should be maximized between it and the provider trying to remove it using forceps or other long surgical instrument. Removed tissue, foreign bodies, and instruments used to remove them should be collected and labeled with identifiers as radioactive and stored.

External contamination of the facial orifices poses risk of internal contamination. Decontamination of the eyes with irrigation can be used if the globe is not ruptured, but run-off must be directed away from the nose and mouth and prevented from entering the ears. Blowing the nose can facilitate decontamination. If necessary and tolerated, the nares can be irrigated if doing so does not force more contamination into the body. The mouth can be decontaminated by brushing with toothpaste, mouth rinsing, and gargling with 3% hydrogen peroxide. Decontamination of the ear canal should involve irrigation only if the tympanic membrane is visualized to be intact. In all these cases, irrigation fluid can be collected, labeled, and stored.

Hairy areas can be washed with tepid water and mild soap or shampoo, even repeatedly. Conditioner should not be used, as it may bind radiation particles to hair. Run-off should be directed away from the patient to avoid further contamination. Hair can be clipped if necessary but should not be shaved.

Decontamination of intact skin should proceed using techniques from least to most aggressive to balance potential injury with removal of external radiation. It should avoid abrasions that may allow increased entry of external contamination. Dry decontamination can be attempted first, especially if water is limited. The skin can be brushed gently to dislodge radioactive particulates. Adhesive tape (masking tape, not duct tape) can be pressed onto a contaminated area to lift off the contaminant, but this should not be performed on hairy areas or fragile tissue like eyelids. Alternatively, the skin can be washed with tepid water and mild soap for 1 to 3 minutes to float contaminants off the skin and rinse them away. Care should be taken not to splash contaminated water, and run-off should be collected, labeled, and stored.

Minimally aggressive methods include use of baby wipes and application/removal of waterless hand cleaner to a small area. If gentler methods are not effective, gentle scrubbing can be performed using a soft cloth or soft surgical scrub brush. Serial cloths or brushes should be used to avoid recontamination. Decontamination of intact skin should be discontinued if erythema develops. In that vein, possibly only 2 decontamination cycles should be performed. If decontamination has not been effective, then the area can be wrapped or covered with a bandage to allow removal of contamination through sweating and skin sloughing. In that case, the bandage must be monitored periodically, changed as necessary, and labeled and stored when removed.

PART 4 – MEDICAL TREATMENT OF INTERNAL RADIATION CONTAMINATION

The goal of internal decontamination is to reduce the risk of future biological effects to the whole body or to a specific organ. This can be achieved in the appropriate clinical context with medications specific to corresponding nucleotides. Consultation with a toxicologist, a poison control center, or a Pediatric Environmental Health Specialty Unit (PEHSU) (www.pehsu.net) can provide expert guidance. Mechanistically, these medications can block uptake of the radionuclide, decrease absorption, change distribution, or enhance elimination. The medications discussed are approved by the US Food and Drug Administration (FDA) and are available in the Strategic National Stockpile, an equipment and pharmaceutical cache operated by the US Department of Health and Human Services for use during a national disaster.

Potassium Iodide to Treat Radioactive Iodine Contamination

A nuclear power plant incident would release radioactive iodine and other radionuclides. Radioactive iodine inhaled or ingested in contaminated food, milk, or water, concentrates in the thyroid gland where it causes thyroid injury and a significantly increased risk of thyroid cancer. The indication for using KI is determined by the predicted thyroid dose. Timing of administration is crucial, as treatment within 1 hour of an incident is optimal and after 12 hours is expected to be minimally effective. Hence, KI must be readily available in high-risk areas. Therefore, coordinated advanced distribution of KI to many communities around nuclear power plants has been carried out by the Federal Emergency Management Agency and the Department of Energy.

Children and fetuses are at relatively increased risk of increased radioactive iodine toxicity since the smaller thyroid gland concentrates proportionately more radioactive iodine that that of an adult. Hence, risk-stratified treatment should be indicated preferentially for children and pregnant women.

KI dosing is age dependent. Tablets would need to be dissolved for administration to young children. Because of a salty taste, additives may be necessary to increase palatability. Treatment with KI can cause occasional GI symptoms and rash. Breastfeeding will need to be temporarily suspended because of associated risks of KI therapy in infants and neonates. In neonates, transient hypothyroidism can develop, so thyroid-stimulating hormone level should be monitored every 2 to 4 weeks and supplemental thyroid hormone should be given to those found to have hypothyroidism. Severe reactions include allergy that would be expected to increase with repeat dosing.

Prussian Blue to Treat Radioactive Cesium, Thallium, and Rubidium Contamination

Prussian Blue, ferric hexacyanoferrate, is prescribed for the treatment of internal contamination with cesium, thallium, or rubidium. Prussian blue is administered orally. Treatment should start as soon as possible after contamination is suspected and should continue for a minimum of 30 days. Side effects are rare, the most common of which is mild to moderate constipation.

DTPA to Treat Radioactive Plutonium, Americium, and Curium Contamination

Diethylenetriamine pentaacetate (DTPA) is a chelating agent that can remove heavy metal isotopes. Both calcium-DTPA and zinc-DTPA can be used to increase rates of elimination for

people with known or suspected internal contamination with plutonium, americium, or curium. These chelators should not be used in case of internal contamination with uranium because of risk of renal toxicity. Instead, bicarbonate should be used to alkalinize urine to promote excretion.

Calcium-DTPA is more immediately effective than zinc-DTPA but has increased side effects. Calcium-DTPA should be started on the first day of treatment and then transitioned to zinc-DTPA thereafter. However, pregnant women should be given zinc-DTPA starting from the first day. Both medications are given IV daily. Few serious side effects are reported for these medications, but nausea, vomiting, diarrhea, chills, fever, pruritus, and muscle cramps have been noted in the first 24 hours when given repeatedly.

PART 5 – DIAGNOSIS OF RADIATION EXPOSURE

The effects of radiation exposure vary by dose, rate, and extent of exposure. (See also Figure 7.5). Dosimetry allows the best dose estimate, with implications for management of complications like acute radiation syndrome and cutaneous radiation injury. Exposure to ionizing radiation induces cellular damage directly by interacting with cellular components or indirectly through production of free radicals and other harmful molecules. Physiologically, radiation exposure causes depletion of stem cells and microvascular injury. The biological impact of radiation exposure is apparent both acutely and in the long term. Acute effects cause delay in cell division and promotion of cell death. Late effects include fibrosis and carcinogenesis.

Dosimetry

Biodosimetry is the use of a biological response as an indicator of radiation dose. It is a crucial element of evaluation for any patient with possible radiation exposure. Ideally, laboratory evaluation should include a complete blood count with white blood cell differential, sent every 6 hours for 48 hours. Decrease in the value of the absolute lymphocyte count can be used to estimate radiation dose. An increase in the neutrophil to lymphocyte ratio is anticipated to occur over 2 days after radiation exposure. If resources are limited, estimates of dose exposure can be performed with 1 or 2 complete blood cell counts.

Cytogenetic biodosimetry is the standard for detecting chromosomal changes after radiation exposure. It is sensitive and specific within days to about 6 months. There are various permutations, including the dicentric chromosome analysis, which counts chromosomes with 2 centromeres in stimulated lymphocytes after arrest in the first metaphase, and employs a previously established dose-response curve.

The Armed Forces Radiobiology Research Institute suggests obtaining the following, if feasible:

- C-reactive protein (CRP), which increases with dose
- Serum amylase at presentation and at 24 hours which is expected to rise in a dose-dependent way after radiation exposure
- Blood FLT-2 ligand levels as marker for hematopoietic damage
- Blood citrulline as decreasing levels indicate GI tract damage
- Interleukin-6 (IL-6) as a marker increased at higher radiation dose
- Quantitative granulocyte colony stimulating factor (G-CSF) as a marker increased at higher radiation dose

When rapid diagnosis is required to predict the need for treatment, time to onset of vomiting and speed of lymphocyte depletion on serial testing of blood tests can be used. Interindividual variability is great, but these tests can be sensitive even if not highly specific.

At a time removed from the incident, multiparameter dose assessment could be performed with knowledge of the patient's field history (where the patient was at the time of the event and afterwards, whether the patient was shielded, what the patient ate or drank, etc), including signs and symptoms, radioactivity assessment, hematologic parameters, personal and area dosimetry, cytogenetics, and other laboratory testing. Over time, as more information about the event is learned and as patient testing results return, the dose estimate of exposure may be able to be refined.

Medical Issues: Acute Radiation Syndrome

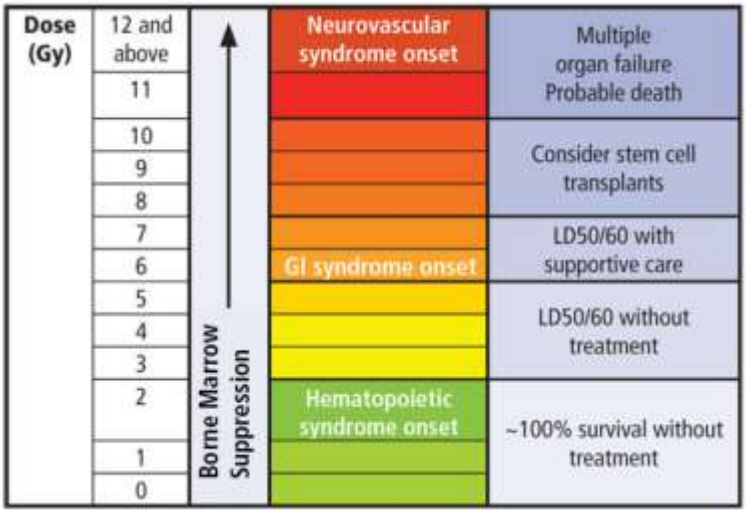

Figure 7.5. Radiation dose dependent medical presentation and outcome

From: Military Medical Operations. Armed Forces Radiobiology Research Institute. *Medical Management of Radiological Casualties*. 4th ed. Bethesda, MD: Armed Forces Radiobiology Research Institute; 2013. Accessed February 24, 2022.

Clinically, radiation exposure results in ARS. ARS occurs when the radiation dose is large, external, penetrating, affecting the whole body, and delivered in a short time. Patients experience an acute illness with signs and symptoms starting within hours to weeks. Radiation exposure of significant dose to cause ARS would occur after a nuclear explosion but not a radiological dispersal device.

Clinical stages of ARS include the prodromal stage that starts within minutes to days, a latent stage without symptoms that can last from hours to weeks, and then the manifest illness stage that can last for hours to months and is characterized by various subsyndromes - each affecting a different organ system. The subsyndromes appear in a stereotyped order, affecting the hematologic, gastrointestinal, and cardiovascular/central nervous systems. The subsyndromes are

progressive in that higher doses are associated with worse symptoms, especially in the hematologic and gastrointestinal systems. The subsystems are also additive, as higher doses are associated with involvement of more subsyndromes. Full expression of the manifest illness stage is followed by recovery over months or death.

Hematopoietic Subsyndrome
The blood system shows effects with exposure to ionizing radiation greater than 0.7 Gy. Clinical severity increases with dose such that pancytopenia occurs at 2 Gy and supportive care would be required for survival. Leukopenia, fall in lymphocytes and granulocytes, can result in increased risk of viral, fungal, and bacterial infections. Thrombocytopenia can result in increased risk of spontaneous bleeding. Anemia can result in hemodynamic compromise.

Gastrointestinal Subsyndrome
The GI system shows effects with exposure to ionizing radiation greater than 5 Gy. Where exposure to ionizing radiation greater than 8 Gy, it is likely lethal without supportive care. The prodrome can be severe and may be followed by a latent period of 5 to 7 days. Enteropathy is the clinical presentation with ileus that may cause abdominal distention, vomiting/diarrhea that can cause dehydration, decreased tissue integrity and bleeding in association with leukopenia and thrombocytopenia as described above, and death resulting from bacterial infection and sepsis.

The Cardiovascular and Central Nervous System Subsystems
The cardiovascular and central nervous system (CNS) subsystems are affected at greater than 20 Gy and reach full penetrance at >50 Gy. At these high doses of radiation exposure, cerebral edema can ensue in minutes with altered mental status progressing to seizures. A latent period of 2 days may ensue, during which orthostatic hypotension and weakness present. Ultimately, coma and death resulting from cerebral edema occur over several days. Other symptomatology may ensue over time, as radiation exposure >5 Gy can present weeks later with radiation pneumonitis.

An interactive tool based on METREPOL guidance (MEDical TREatment ProtocOLs) for Radiation Accident Victims is found on the Radiation Emergency Medical Management (REMM) website (https://remm.hhs.gov/). Symptoms of ARS are used to estimate radiation exposure and to offer recommendations regarding prognosis/follow-up.

Surgical Issues: Cutaneous Radiation Injury, Embedded Radioactive Material
Cutaneous radiation injury (CRI) describes damage to the skin and underlying tissues attributable to exposure to radiation. CRI may occur alone, as after exposure to a minimally penetrating source or external contamination of clothing or skin, or it could complicate ARS. In the case of combined CRI and ARS, morbidity and mortality could be attributable to CRI causing a progressive and complex inflammatory process including fever, metabolic disorders, and neurologic side effects resulting from release of endogenous factors.

Visible changes in the skin reflect both the dose and depth of penetration of radiation exposure. Although a small superficial area may show damage, deeper tissues and organ systems may be affected. Skin damage evolves, with tissue furthest from the most affected area showing damage later. CRI tends to appear in cycles that can occur over months or years.

A prodromal erythematous stage occurs minutes to hours after exposure and may last for a few days. Symptoms include erythema, heat, and itching. Time to onset, intensity, and duration of changes may aid prognosis. Early erythema likely is attributable to release of vasoactive amines and secondary vasodilation.

A clinically asymptomatic latent stage may follow for 7 to 21 days. The length of the latent period is inversely proportional to the dose. Concurrent symptoms of ARS would suggest whole body irradiation in addition to cutaneous injury.

A manifest illness stage occurs days to weeks after exposure characterized by bright erythema accompanied by a burning sensation, heat, and edema, as well as increased pigmentation. Depending on severity, dry desquamation or ulceration to necrosis may occur. These findings are attributable to injury to blood vessels and underlying connective tissue. Radiation-sensitive areas of the body like axillae, groin and skin folds may be more affected than less radiation-sensitive ones such as the neck, palms, and soles. Wound infection with bacteria, fungi, or viruses is possible during this stage. Prevention and treatment are key. If affected areas are extensive, care in a burn unit may be necessary.

The subacute stage follows 10 to 16 weeks after exposure. This is characterized by late erythema, blood vessel injury, edema, and pain. There is initiation of progressive dermal and subcutaneous fibrosis.

Finally, a chronic stage usually starts from 16 weeks to 2 years after initial injury, with symptoms that range from mild dermal atrophy to ulcers, dermal necrosis, and deformity. This stage is characterized by dermal fibrosis and subcutaneous sclerosis of connective tissue. Ultimately, the inflammation progresses indefinitely such that long-term evaluation and management are indicated.

Lastly, a late stage 10 to 30 years after exposure results in development of angiomas, keratoses, ulcerations, and squamous and basal cell carcinomas.

With respect to treatment, ulceration and localized necrosis without regeneration may require surgical intervention. Rapid progression suggests increased tissue injury and should encourage earlier intervention, which is intended to remove injured and dead tissue to allow effective engraftment.

Antihistamines and topical anti-pruritic agents may be used for relief of symptoms and may attenuate the inflammatory process. High-dose systemic glucocorticoids with topical class III or IV steroids should be considered.

PART 6 – MEDICAL TREATMENT OF RADIATION EXPOSURE

Treatment for radiation exposure includes both general supportive care and therapy directed at specific symptoms. These therapies are modeled after those for patients who have been treated with chemotherapy or radiation.

Gastrointestinal Support: Anti-emetics, Hydration, and Nutrition
The earliest clinical symptoms of radiation exposure are manifestations of the GI subsyndrome including nausea, vomiting, and diarrhea. Nausea and vomiting can be treated with antiemetics like ondansetron and granisetron, at doses used to manage chemotherapy-induced symptoms. Antiemetics may be contraindicated initially if catharsis is necessary for internal decontamination of ingested radioactive material. Anti-diarrheal agents generally should not be given because of concern for worsening possible infection.

Fluid losses through the GI tract can be severe or prolonged enough to cause dehydration resulting from hypovolemia. Further, fluid intake may be limited with anorexia. Intravenous fluids may be required intermittently or continuously to maintain fluid balance. Monitoring of electrolytes and their repletion should be carried out as clinically indicated.

Nutritional intake may need to be supplemented if oral intake is insufficient. Continued enteral feeding, either orally or via nasogastric tube, is preferred to maintain functioning of intestinal mucosa and to avoid infectious risk of parenteral feeding. If enteral feeding is not possible because of anorexia or is not tolerated because of continued vomiting or diarrhea, then parenteral feeding may be necessary. Nutritional repletion is necessary to counter catabolic effects of radiation and to promote healing.

Hematologic Support
Early laboratory manifestations of radiation exposure are apparent in the hematologic subsyndrome. Lymphocyte depletion can start to occur immediately. Pancytopenia with neutropenia, thrombocytopenia, and then anemia can arise over days to weeks. Neutropenia is associated with a risk of sepsis and death, thrombocytopenia with bleeding, and anemia with complications of decreased oxygen-carrying capacity. Each of the therapies described is intended to improve blood count or prevent infection.

Growth Factors to Treat Neutropenia
Based on experiences of chemotherapy patients as well as preclinical animal studies, early cytokine therapy can promote neutrophil recovery. Hematopoietic growth factors, granulocyte colony stimulating factor (G-CSF, filgrastim) or pegylated G-CSF (peg-filgrastim) or granulocyte macrophage colony stimulating factor (GM-CSF, sargramostim), have been approved by the FDA for management of marrow aplasia after exposure from a radiation incident. They should be given as early as possible after radiation exposure and continued until the absolute neutrophil count rises to 1000×10^6 cells/L post-nadir. Granulocyte transfusions are problematic and not indicated for neutropenia attributable to radiation exposure.

Blood Product Transfusions to Treat Thrombocytopenia and Anemia
Transfusion of life-sustaining blood products may be necessary for patients with profound cytopenias resulting from the hematologic subsyndrome after radiation exposure. Blood type and screen should be kept current. Institutional protocols govern procedures for blood bank staff and clinicians with respect to blood typing and obtaining consent for transfusion. Transfusions carry risks that include hemolytic reactions, febrile reactions, allergic reactions, and infections.

Thrombocytopenia results when the number of megakaryocytes in the bone marrow that give rise to peripheral blood platelets are reduced. When the platelet count falls below some threshold (often 10-20 x 10^6 cells/mL) or the patient has symptoms of thrombocytopenia like bleeding, then platelets should be transfused. Platelet units should ideally be from single donors to limit the number of exposures and hence to decrease risk of alloimmunization. Platelet transfusion may typically be required every 1 to 2 days or possibly even more frequently.

Anemia results when production of red blood cell precursors in the bone marrow is decreased. When the hemoglobin level falls below some threshold (often 7-8 g/dL) or the patient has symptoms of anemia like tachycardia or hypotension or poor perfusion, then a red blood cell transfusion with appropriately typed and cross-matched blood should be given. In the current era, blood products must be leukoreduced to minimize risk of cytomegalovirus (CMV) transmission and irradiated to eliminate risk of engraftment of donor leukocytes that could cause transfusion-associated graft-versus-host disease. Packed red cell transfusion may typically be required every 2 to 3 weeks; more in the presence of blood loss because of bleeding.

Management of Neutropenic Fever

Febrile neutropenia after radiation exposure should be managed like that after chemotherapy, where bacteremia and septic shock are feared complications.

People exposed to radiation are at risk of febrile neutropenia. Each institution has guidelines about a standard plan for management of patients that is informed by local bacterial susceptibilities and nosocomial infections. With fever, broad spectrum empiric antibiotics should be started with coverage for gram negative bacteria most likely to cause sepsis in this context.

If a specific bacterial organism is identified as the cause of fever, then the empiric regimen may be adjusted and a treatment course should be completed, usually for at least 7 days and possibly until sometime after resolution of neutropenia. If the identified organism is not sensitive to the empiric antibiotics given, then the regimen must be adjusted or can be tailored to the identified organism and susceptibility.

If fever persists, then a search for another source or type of infection may be indicated. Viral infections such as herpes simplex can cause oral and pharyngeal ulcerations that mimic radiation-induced mucositis. Fungal infections can be attributable to *Candida* infection, causing thrush or disseminated disease. If fever and neutropenia persist despite empiric antibacterial therapy or recur on antibacterial therapy, then broadening of antifungal coverage to include *Aspergillus* infection or molds and investigation for fungal infection should be considered.

Infectious disease specialists who specialize in caring for immunocompromised patients may provide expertise in preventing and treating their infections.

Prophylactic Antibiotics

According to recommendations of the RITN, people with neutropenia after radiation exposure should receive prophylactic antibacterial, antiviral, and antifungal agents. Levofloxacin is recommended for anti-bacterial prophylaxis. Acyclovir is recommended for herpes simplex virus or vaccinia virus prophylaxis. Fluconazole or posaconazole is recommended for antifungal

prophylaxis. Supplements to prophylactic antibiotics include screening for infections that can arise in spite of prophylaxis.

Hematopoietic Stem Cell Support for Select Patients
After a radiation event, a subset of people will have had sufficient radiation exposure to cause pancytopenia and limited traumatic or other injuries. In that situation, transplantation of allogeneic (another person's) hematopoietic stem cells – from bone marrow, peripheral blood, or conceivably cord blood – could be considered. Hematopoietic stem cell transplant has been used for radiation injury, with poor results. Limitations of transplantation include challenges with time to identify a donor, risks of conditioning with chemotherapy/immunotherapy, infection and organ toxicity, and risk of graft-versus-host disease.

To date, no cellular therapies have been approved for treatment of the hematologic subsyndrome of ARS. The recommendation of an international consensus conference to address this issue in 2009 was to administer allogeneic hematopoietic stem cell transplantation only in cases where there are no signs of endogenous bone marrow recovery. Preclinical animal models of radiation injury are being used to test possible roles for different cellular therapies to treat specific organ toxicities.

PART 7 – ISSUES UNIQUE TO PEDIATRICS

Children may face unique challenges after a nuclear or radiological event. Some challenges are based on observational studies after prior events. Others are projected challenges based on differences in physiology between adults and children.

Susceptibility to Radiation Contamination
Several factors cause children to be more susceptible to both external and internal contamination.

External contamination risk is amplified for crawling infants and toddlers who have increased proximity to residual radiation on the ground; older children may climb on playground equipment that has not be fully remediated.

With respect to inhalation, there is concern that children have increased vulnerability from fallout because of their higher baseline respiratory rates and a lower breathing zone; however, modeling suggests that this risk likely holds only for iodine 125I and 131I and because of their smaller thyroid glands and higher thyroid uptake rather than respiratory differences.

Several factors may influence internal contamination by ingestion. Children are more likely to put their hands up to and in their mouths and to engage in hand-to-mouth activity with radioactive particles, leading to internal contamination via ingestion. Risk of ingestion depends on dietary intake, because milk is a staple of childhood diet. Anticipated amplification in cow milk through the grass-cow-milk pathway suggest that milk from cows that graze on contaminated grass should be banned during the first weeks following an event; canned milk produced prior to the event or away from the site should be safe. Human milk can be contaminated with radioactive iodine, so in the case of contamination, breastfeeding should be discontinued until reported to be safe, while human milk that was frozen before an event would not be contaminated.

Of note, if acceptable levels for food contamination are based on adult intake, this level may not optimally protect children. For example, strontium and radium substitute for calcium in bone such that adolescents who are undergoing rapid bone growth will have a different pattern of incorporation. Additionally, with respect to treatment, children may have increased risk of side effects like dehydration and electrolyte imbalance or aspiration with drugs that decrease internal contamination. Uptake of radioiodine in the thyroid can be prevented by treatment with potassium iodine. Thresholds of predicted thyroid exposure may be set for children and pregnant or lactating women; side effects were discussed previously.

Susceptibility to Radiation Exposure: Acute and Long-Term Issues

Children have physiologic features that make them more vulnerable to acute injury following a nuclear detonation. After a nuclear blast, young children may be more vulnerable to burns because of less keratinization and increased permeability of their skin. They may have increased risk of ophthalmologic injury because of an inability to shield their eyes from pressure, heat, and light. Children may be more vulnerable to effects of residual or fallout radiation because of their closer proximity to the horizontal surface of the ground. For infants especially, their greater body surface area to weight ratio than adults may result in more damage from the same dose because of reduced self-shielding of vital organs.

Fetuses have different risks following radiation exposure during gestation. This difference may be direct through exposure or indirect exposure following contamination and concentration in maternal tissue or contamination with subsequent crossing of the placenta and concentration in the fetus. Radiation effects are dependent on dose and gestational age. Failure to implant, miscarriage, or neonatal death are possible outcomes. Exposure before 2 weeks is unlikely to cause non-cancer health effects if the embryo survives. There is a threshold below which radiation-induced non-cancer health effects are not detectable. Especially during the first trimester, surviving fetus may develop intellectual disabilities and microcephaly resulting from brain development effects and postnatal growth restriction. The level at which non-cancer effects are unlikely is higher from 16 weeks' gestation onward.

Children are more susceptible than adults to risks of malignancy over the same latent period. Additionally, they have a longer lifetime ahead and hence a longer period of latency. Cellular factors like differences in stem cell replication and differences in chromosome damage after radiation exposure may explain why children are more vulnerable to long-term effects of radiation. Planned follow-up should continue for a longer time, as children have a higher lifetime risk of certain cancers. Other risks related to external or internal radiation exposure, like changes in the skin or lungs, are anticipated but less well described.

With respect to risk of malignancy after radiation exposure, follow-up of people exposed after prior nuclear or radiation events has been informative. Leukemia incidence is noted to be twice as high in children as adult survivors; this risk begins within 2 years, reaches its peak at 6 years, and regresses to baseline after 25 years. Leukemias seen in children are chronic myelogenous leukemia and acute myelocytic leukemia.

Thyroid malignancy incidence begins within 4 years after ingestion or inhalation and continues. The risk is higher for those younger than 20 years of age versus those older. Notably, children born 9 months after the event are not affected.

Breast cancer incidence was increased for females 10 to 19 years of age at the time of radiation exposure relative to those 20 years of age and older, with a latency of 10 years described. Interestingly, breast cancer incidence was higher also for females younger than 10 years.

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