AMERICAN ACADEMY OF PEDIATRICS

POLICY STATEMENT

Organizational Principles to Guide and Define the Child Health Care System and/or Improve the Health of All Children

Committee on Environmental Health

Radiation Disasters and Children

ABSTRACT. The special medical needs of children make it essential that pediatricians be prepared for radiation disasters, including 1) the detonation of a nuclear weapon; 2) a nuclear power plant event that unleashes a radioactive cloud; and 3) the dispersal of radionuclides by conventional explosive or the crash of a transport vehicle. Any of these events could occur unintentionally or as an act of terrorism. Nuclear facilities (eg, power plants, fuel processing centers, and food irradiation facilities) are often located in highly populated areas, and as they age, the risk of mechanical failure increases. The short- and long-term consequences of a radiation disaster are significantly greater in children for several reasons. First, children have a disproportionately higher minute ventilation, leading to greater internal exposure to radioactive gases. Children have a significantly greater risk of developing cancer even when they are exposed to radiation in utero. Finally, children and the parents of young children are more likely than are adults to develop enduring psychologic injury after a radiation disaster. The pediatrician has a critical role in planning for radiation disasters. For example, potassium iodide is of proven value for thyroid protection but must be given before or soon after exposure to radioiodines, requiring its placement in homes, schools, and child care centers. Pediatricians should work with public health authorities to ensure that children receive full consideration in local planning for a radiation disaster.

ABBREVIATIONS. TMI, Three Mile Island; KI, potassium iodide; SI, International System of Units; CT, computed tomography (scan); NRC, Nuclear Regulatory Commission; FDA, Food and Drug Administration.

INTRODUCTION

Several large-scale radiation disasters have befallen children in the past, including the detonation of nuclear bombs in Hiroshima and Nagasaki, Japan; the nuclear power plant disaster in Chernobyl; and exposure to a cesium-127 source scavenged from an abandoned hospital in Brazil. In each case, postevent medical surveillance proved that children were disproportionately affected after radiation exposure.

In recent years, accidents at several nuclear power plants have proven such events can lead to the widespread discharge of radioactive materials into the environment. Additionally, acts of domestic terrorism involving chemical and biological weapons have recently occurred, raising fears about the intentional use of a radioactive device against a civilian population that includes children. Because of these threats, there is a need for pediatricians to become more informed about the issues that would occur in the case of a significant radiologic event.

HISTORY

Several historical events have shaped our understanding of the consequences of radiation disasters. The atomic bomb blasts in Hiroshima and Nagasaki in 1945 during World War II remain the most defining moments in the consequences of a nuclear exposure. The Avalon Project at Yale Law School[1] estimated that in Hiroshima, the bomb released power equal to 15 kilotons of trinitrotoluene (TNT), killing an estimated 66 000 and injuring 69 000 of the 255 000 exposed. The Nagasaki release, containing a 22-kiloton force, killed an estimated 39 000 among the 195 000 exposed. In 1954, fallout from nuclear weapons tests on Bikini Island fell on neighboring islands, producing significant health effects in children; of 32 Marshallese exposed to fallout before 20 years of age, 4 developed thyroid cancer and 1 developed leukemia.[2] This event led the American Academy of Pediatrics to establish the Committee on Radiation Hazards and Congenital Malformations, the predecessor to the Committee on Environmental Health.[2]

On March 28, 1979, a nuclear power plant, Three Mile Island (TMI), had a near "meltdown" (overheating of the fuel rods and a release of radiation) that produced negligible doses among people living nearby: a maximum of 0.001 Sv (100 mrem) and an average dose to the community of 0.00001 Sv (1 mrem).[3] The TMI accident brought into question the safety of nuclear power plants and the potential consequences of a power plant mishap.[4,5] Immediate administration of potassium iodide (KI) was recommended for those living near TMI, but it was not available. There were no biological effects of the exposure but significant psychologic sequelae occurred.[4,5]

In April 1986, a power plant in Chernobyl (also known as Chornobyl), Ukraine, had a mishap that produced a meltdown. The area around the reactor was heavily contaminated with plutonium, cesium, and radioactive iodine. An estimated 120 million Ci of radioactive material were released, contaminating more than 21 000 km^2 of land, with the greatest areas of fallout occurring in Ukraine, Belarus, and the Russian Federation.[6,7] Approximately 135 000 people were permanently evacuated.[8] A total of almost 17 million people, including 2.5 million younger than 5 years of age, were exposed to excess radiation.[7] The first delayed effect, beginning 4 years after exposure, was the occurrence of a great excess of cases of thyroid cancers in children and adolescents, especially among those younger than 4 years of age at the time of the accident.[9] Seventeen years later, the area remains uninhabited because of persistent concerns about environmental contamination.

On September 13, 1987, in Goiania, Brazil, a lead canister containing 1400 Ci of radioactive cesium was left in a building when it was abandoned by radiotherapists. The canister was taken and opened by looters. Children played with the material inside, rubbing it on their bodies so they glowed in the dark.[10] An estimated 250 people were exposed, with some receiving radiation doses as high as 10 Sv (1000 rem); 4 died of acute radiation sickness.[11] Victims developed radiation-associated illnesses that ranged from significant skin injury (radiation burns) to acute radiation sickness to long-term health problems. Thousands of people rushed to emergency departments because of fear of contamination.[10] Mitigation efforts required the removal of 6000 tons of clothing, furniture, dirt, and other materials.[12]

SOURCES OF POTENTIAL RADIATION EXPOSURE

Humans are exposed to an estimated average of 0.0036 Sv (360 mrem) of radiation annually. This radiation exposure comes from a number of natural and manmade sources, including cosmic radiation and radon, cigarette smoke, medical devices, home appliances, and pharmaceutical agents. Air flight is associated with cosmic radiation exposure; a flight from New York to London results in an estimated 0.00005 to 0.0001 Sv (5–10 mrem) of radiation exposure. Radiation exposure from medical radiography can range from 0.00005 to 0.0001 Sv (5–10 mrem) for a chest radiograph to as much as 0.05 Sv (5000 mrem) for computed tomography (CT).[13]

Radiologic threats can be unintentional or intentional. Unintentional threats include power plant disasters such as Chernobyl and TMI. Intentional threats are associated with military conflict or terrorism. Three major types of radiation disaster threats are 1) the detonation of a nuclear weapon; 2) damage of a facility that contains nuclear material (eg, a nuclear waste reprocessing facility, food irradiation plant, or nuclear power plant); and 3) dispersal of nuclear material, either by detonation of a conventional explosive (a radioactive dispersal device or "dirty bomb") or the release of nuclear materials in transit. Any of these occurrences could result from human error or terrorist activity.

Terrorist use of a radioactive dispersal device is considered the most likely present-day threat.[14] Radioactive dispersal devices are designed to use radioactive material obtained from relatively accessible sources, such as university research laboratories or hospital radiation therapy centers.[14,15] Although they would not produce significant damage to nearby structures, these devices could render an area uninhabitable; as little as 1 Ci of radioactive material can be dispersed several blocks, forcing evacuation and closure of that area.

In the United States, there are 103 active nuclear reactors in 66 power plants across 31 states.[16] Nuclear power plants pose several distinct radiation risks. The most important of these risks is the potential for release of radioiodines into the environment. Additionally, spent reactor fuel rods, which are typically retained by the nuclear power plant for many years, present a radiation hazard that is distinct from an incident that releases a radioactive cloud.

Since the 1990s, the possibility of a terrorist group creating a nuclear weapon has become more possible.[17] A low-yield detonation device (<10 kilotons) would require only a small amount of plutonium or highly enriched uranium, both of which are thought to be obtainable in the current era.[10]

RADIATION CHARACTERISTICS AND TERMINOLOGY

Unstable atoms, in an effort to achieve stability, emit energy in the form of ionizing radiation. Ionizing radiation is a type of high-frequency energy that has adverse biologic effects, including damage to DNA, production of free radicals, disruption of chemical bonds, and production of new macromolecules.[17,18] Ionizing radiation can be particulate and electromagnetic. Radionuclides, elements that emit ionizing radiation, exist naturally (eg, uranium) or can be manmade (plutonium).

There are 5 types of ionizing radiation: α-particles, β-particles, γ-rays, x-rays, and neutrons.[14] Each has different characteristics and behaviors. α-Particles consist of 2 protons and 2 neutrons; they are extremely heavy with a limited ability to penetrate clothing or skin. However, when inhaled or ingested, they can penetrate epithelial tissue layers to a 50-μm depth, sufficient to produce cellular injury (explaining the association between the α-emissions of inhaled radon and development of lung cancer). β-Particles, consisting of electrons only, have greater penetrance than do α-particles. They can produce internal injury when inhaled or ingested as well as skin injury. Unlike α-particles, which originate primarily from natural sources, β-particles most commonly come from radionuclides used in medicine (eg, xenon) or created as by-products of nuclear reactors (eg, radioactive iodines).[19] Neutrons are a powerful but uncommon type of radiation, emitted only after a nuclear detonation. Neutrons are highly destructive, producing 10 times more tissue damage than γ-rays produce.[15]

γ-Rays and x-rays are part of the electromagnetic spectrum. Unlike α- and β-particles, these rays have no mass. γ-Rays are emitted from radioactive materials, including cesium and cobalt, or after a nuclear detonation. Having high energy and no mass, γ-rays are highly penetrant. X-rays, which are unlikely to be encountered in a radiation disaster, transfer energy along shorter paths with little scatter, whereas neutrons have greater mass and transfer energy along longer paths.

The units of measure of energy absorbed from x-rays and γ-rays are the rad (radiation absorbed dose) and the rem (roentgen equivalent man—a weighting or quality factor). The rem is based on greater relative biologic effectiveness (RBE) of doses from particulate radiation, such as neutrons. Thus, (rem) = (rad) × RBE. The rad and rem have been replaced by Gray (1 Gy = 100 rad) and Sievert (1 Sv = 100 rem), respectively, in accordance with the International System of Units (SI). The unit of activity for radiation emission of a radionuclide is Ci (curie) or, in SI, the Becquerel (Bq). These units and other terminology are summarized in the Appendix. The radionuclides and radioactive emissions associated with a radiation disaster are listed in Table 1.

CONSEQUENCES OF A RADIATION DISASTER

Radiation Biology

Radiation exposure can be divided into external, internal, whole body, or partial body. Internal irradiation can occur after inhalation of a radioactive gas or ingestion of contaminated food (including produce, grains, and milk from goats or cows that have been grazing on contaminated fields). Radiation effects can be direct, interacting with target tissues; or indirect, producing free radicals or other harmful molecules. The cellular effects of radiation are highly variable, correlating directly with the cell's typical rate of division and inversely with the extent of cell differentiation.[14] The sensitivity of tissues to radiation, from most to least, is: lymphoid > gastrointestinal > reproductive > dermal > bone marrow > nervous system. Ionizing radiation produces chromosome breaks in a variety of somatic cells; these breaks can persist for decades after exposure and may account for increased rates of cancer after irradiation. Other significant modulators of cellular injury after radiation exposure include dose, type of radiation, and age of the exposed person.[17]

Health Effects

Health effects after a radiation exposure will depend greatly on the circumstances surrounding the release. For example, after detonation of a nuclear weapon or radioactive dispersal device, there may be thermal or blast injury in addition to radiation exposure. In contrast, a nuclear power plant disaster can produce a radioactive cloud with no associated blast.

Specific health outcomes after radiation exposure are typically divided into short-term and long-term; short-term effects appear within days to weeks after exposure, and long-term effects appear months to years later. Short-term effects are dependent on the degree of radiation exposure and the tissue irradiated. Nausea and vomiting appear after exposures as little as 0.75 to 1.0 Gy (75–100 rad); a hematopoietic syndrome (severe lymphoid and bone marrow suppression) typically appears after 3.0 to 6.0 Gy (300–600 rad) exposures and may cause death in 8 to 50 days. Postirradiation lymphocyte counts correlate strongly with dose received; if the lymphocyte count decreases by more than 50% within 24 to 48 hours, a moderate radiation exposure or worse has occurred. Bone marrow and lymphoid depression lead to anemia and an increased risk of infection; the decrease in platelets can lead to generalized bleeding.[15] The mean lethal dose ($LD_{50/60}$), that is, the radiation dose for which 50% of an exposed population would be expected to die within 60 days, is 4.0 Gy (400 rads). Long-term effects (described below), include psychologic injury and increased cancer risk.

VULNERABILITIES IN CHILDREN

Children have a number of vulnerabilities that place them at greater risk of harm after radiation exposure. Because they have a relatively greater minute ventilation compared with adults, children are likely to have greater exposure to radioactive gases (eg, those emitted from a nuclear power plant disaster). Nuclear fallout quickly settles to the ground, resulting in a higher concentration of radioactive material in the space where children most commonly live and breathe. Studies of airborne pollutants are needed to test the long-held belief that the short stature of children brings them into greater contact than adults with fallout as it settles to earth. Radioactive iodine is transmitted to human breast milk, contaminating this valuable source of nutrition to infants. Cow milk, a staple in the diet of most

TABLE 1. Radionuclides Produced After a Radiation Disaster

Element	Symbol	Source	Radiation	Respiratory Absorption	Gastrointestinal Absorption	Primary Toxicity	Treatment
Americium	^{241}Am	NWD	Alpha	75%	Minimal	Skeletal, liver deposition, bone marrow suppression	DTPA, EDTA
Cesium	^{137}Ce	MF	Beta, gamma	Complete	Complete	Whole body irradiation	Prussian blue
Cobalt	^{60}Co	MF, FI	Beta, gamma	High	<5%	Whole body irradiation	Supportive
Iodine*	^{131}I	NWD, NPP	Beta, gamma	High	High	Thyroid ablation, cancer	Potassium iodide
Phosphorous	^{32}P	MF	Beta	High	High	Rapidly dividing cells	Aluminum hydroxide antacids
Plutonium	$^{238,239}Pu$	NW, NWD	Alpha, gamma	High	Minimal	Lung, bone, liver	DTPA, EDTA
Strontium	^{90}Sr	NWD	Beta, gamma	Limited	Moderate	Bone-follows calcium	Supportive

Adapted from Jarrett DG. *Medical Management of Radiological Casualties*. Bethesda, MD: Armed Forces Radiobiology Research Institute; 1999.

NWD indicates nuclear weapon detonation; DTPA, diethylenetriaminepentaacetic acid; EDTA, edetic acid (ethylene-dinitrillo tetraacetic acid); MF, medical and research facilities; FI, food irradiation facilities; NW, nuclear reactor waste sties; NPP, nuclear power plants.

* There are numerous radioiodines, including ^{132}I. However, ^{131}I is the most prevalent and clinically important radioisotope.

children, can also be quickly contaminated if radioactive material settles onto grazing areas.

In utero exposure to radiation also has important clinical effects, depending on the dose and form of the radiation; transmission of radionuclides across the placenta may occur, depending on the agent. After exposures to external radiation, fetal doses of 0.60 Sv (60 rem) have produced small head size and mental retardation (in Japanese atomic bomb survivors), when exposures occurred between 8 and 25 weeks of gestational age.[2] A dose-response effect was found in the occurrence of small head size without mental retardation, which occurred in fetuses exposed to ≥0.2 Sv (≥20 rem) between weeks 4 and 17 of gestation.

Radiation-induced cancers occur more often in children than in adults exposed to the same dose. Finally, children also have mental health vulnerabilities after any type of disaster, with a greater risk of long-term behavioral disturbances.[20–22]

MANAGEMENT

A radiation disaster would be followed by a massive, integrated federal, state, and local public health response. Relevant consequence management agencies at a federal level would include the US Department of Homeland Security, the Environmental Protection Agency, the Federal Emergency Management Agency, the Nuclear Regulatory Commission (NRC), the Department of Energy, and the Department of Justice. State and local departments of health, working closely with federal agencies, would develop the appropriate local response, for example, initiation of the emergency broadcast system, the implementation of disaster or evacuation plans, recommendations for evacuation versus sheltering, instructions to begin the administration of KI, and the creation of local shelters for displaced families.

Evacuation and Sheltering

Evacuation is the most important action after a radiation release has occurred, particularly after a radioactive cloud release in which there is time to escape exposure. However, in previous power plant mishaps, the radioactive cloud dispersed in minutes, making immediate evacuation impossible. Moreover, given the magnitude of the task of evacuating an entire population, which could include more than 500 000 residents (on the basis of the location of existing plants), evacuation plans may fail. Evacuation can be extremely chaotic, leading to motor vehicle crashes and other injuries, so caution should be exercised. Relocation may be temporary or long-term, depending on the environmental persistence of radioactivity. The decision to recommend rehabitation versus long-term relocation is made by federal, state, and local agencies on the basis of projected radiation dose levels, the environmental persistence of the radionuclide, physical damage to roads and buildings, and other factors that could affect the safety of the population.[23] If evacuation is impossible, a safe place should be sought within the home or another building. For example, the shielding factor (the ratio of dose received inside the structure to the dose which would be received if the structure were not in place[23]) for γ-rays after a radioactive cloud release is 0.9 for a wooden frame structure, 0.6 for a home basement, 0.4 for the basement of a masonry home, and 0.2 for a large office or industrial building.[23] The duration of sheltering required will depend on the extent of environmental contamination. Families should follow the instructions provided through the local emergency broadcasting system.

Treatment

The management of the child who has sustained significant radiation exposure is dependent on the type and degree of exposure as well as the presence of concomitant injuries.[14] Principles of disaster management, including containment, decontamination, prehospital care, and field triage, should be fully employed.[14] The first phase of managing pediatric radiation victims will be to determine if topical decontamination is warranted. Removal of clothing is responsible for more than 90% of the effectiveness of decontamination after a chemical or radiation exposure.[19] With the implementation of disaster protocols, emergency medical services will establish "hot," "warm," and "cold" zones; contaminated victims will be decontaminated in the field and then transported to a health care facility. However, because disaster victims may come to health care facilities by private vehicle, potentially bringing radioactive materials with them, hospitals and urgent care facilities should develop their own plans for management of a contaminated victim. The hospital radiation safety officer is a vital consultant in the management of patients; radiation detection devices should be placed at the site of care. Additionally, a site for the placement of contaminated clothing should be established. The skin should be washed with warm water; measures should be taken to prevent hypothermia. Children with radioactive material embedded in skin should undergo careful débridement that minimizes further tissue injury. Care to skin burns should be minimal; irrigation alone is recommended.[15,23] Irrigation solutions should be collected in containment vessels and disposed of properly.

Children who have no external contamination (eg, those who have inhaled radioactive material) can be treated according to routine protocols. However, biologic fluids, including saliva, blood, urine, and stool, may be contaminated and require special handling precautions.

Initial medical management includes careful assessment of airway, breathing, and circulation, particularly when there is the potential for blast or thermal injury.[14] Surgical intervention, if warranted, should be performed as soon as possible, ideally within 48 hours of irradiation before wound healing and immunity become impaired.[15]

Specific pharmacotherapy for victims of significant radiation exposure is limited; the decision to use these agents should be made after consulting with an authority on clinical management of radiation victims (eg, a consultant from the NRC or a radiation therapist). KI administration is the cornerstone of preventive treatment after known or suspected exposure to radioactive iodine (radioiodines are common by-products of nuclear power plant activities and, therefore, likely to be emitted after a power plant incident).[14] Other drugs have been suggested[14] but have not been proven effective or without serious adverse effects, especially in children.

KI is the same compound used, in smaller quantities, to iodize table salt. When ingested immediately before, during, or shortly after exposure to radioiodines, KI "floods" the thyroid, blocking uptake of inhaled or ingested radioiodines. When taken promptly after a radioiodine release and at proper dose, KI is effective in preventing radiation-induced thyroid effects.[9] The Food and Drug Administration (FDA) currently recommends that KI be administered only after certain levels of radioiodine exposure, on the basis of risk-benefit analyses derived from the Chernobyl disaster, in which more than 18 million children and adults in Poland (immediately adjacent to Ukraine and Belarus) received at least 1 dose of KI.[9,24] The FDA recommends adhering to the guidance about the threshold for intervention and appropriate dosing but also recognizes that ". . . the exigencies of any particular emergency situation may mandate deviations from those recommendations. With that in mind, it should be understood that as a general rule, the risks of KI are far outweighed by the benefits with regard to prevention of thyroid cancer in susceptible individuals."[25]

Children and pregnant or lactating women should begin taking KI if the predicted thyroid exposure, as projected by government sources, is 0.05 Gy (5 rad) or more (Table 2).[9] Short-term adverse effects associated with KI use in Poland were generally mild, consisting of gastrointestinal tract distress or rash.

KI administration to newborns has been associated with evidence of transient decreases in thyroxine along with increases in thyroid-stimulating hormone. The FDA has therefore recommended that newborns who receive KI have their thyroid function monitored. On the basis of the rate of thyroid hormone synthesis in the newborn, monitoring of thyroid function by measurement of thyroid-stimulating hormone activity 2 to 4 weeks later should be sufficient after a single KI dose; longer periods would be needed for newborns who receive more than 1 dose of KI. The FDA has recommended KI for pregnant women for self-protection and for the protection of the fetus.[9] However, repeated KI dosing by pregnant women could produce neonatal hypothyroidism. The risks versus benefits of continued KI dosing by pregnant women depend on the probability of continued radioiodine exposure.

TABLE 2. Guidelines for KI Administration*[9,24]

Patient	Exposure, Gy (rad)	KI Dose (mg)
>40 y of age	>5 (500)	130
18 through 40 y of age	≥0.1 (10)	130
Adolescents 12 through 17 y of age†	≥0.05 (5)	65
Children 4 through 11 y of age	≥0.05 (5)	65
Children 1 mo through 3 y of age‡	≥0.05 (5)	32
Birth through 1 mo of age	≥0.05 (5)	16
Pregnant or lactating women	≥0.05 (5)	130

* KI is useful for exposure to a radioiodine only. KI is given once only to pregnant women and neonates unless other protective measures (evacuation, sheltering and control of the food supply) are unavailable.
Repeat dosing should be on the advice of public health authorities.
† Adolescents weighing more than 70 kg should receive the adult dose (130 mg).
‡ KI from tablets or as a freshly saturated solution may be diluted in water and mixed with milk, formula, juice, soda, or syrup. Raspberry syrup disguises the taste of KI the best. KI mixed with low-fat chocolate milk, orange juice, or flat soda (eg, cola) have an acceptable taste. Low-fat white milk and water did not hide the salty taste of KI.

Radioiodine and KI are secreted into breast milk. For lactating women and their infants, expert consultants have firmly recommended that infants of exposed mothers should not breastfeed because of the risk to exposed infants of additional exposure to radioiodine from breast milk. Exposed women should temporarily cease breastfeeding unless there are no alternatives.[24] (This is contrary to FDA advice suggesting that infants whose mothers receive KI after radioiodine exposure may breastfeed.[9])

The FDA has recommended against repeated dosing of KI in pregnant women and neonates unless other protective measures (ie, evacuation, sheltering, and control of the food supply) are unavailable.[25] Young infants requiring repeat doses of KI should have their thyroid function closely monitored, and therapy with thyroid hormone should be instituted in cases in which hypothyroidism develops.[9] KI should not be given to individuals with known iodine sensitivity or to those with dermatitis herpetiformis or hypocomplementemic vasculitis (both rare conditions associated with an increased risk of iodine hypersensitivity). KI should be used with caution in individuals with thyroid disease (such as multinodular goiter, Graves disease, and autoimmune thyroiditis), especially if dosing extends beyond a few days.[25] Such individuals should have monitoring of thyroid function.

KI is currently made as a 130-mg and a 65-mg tablet. The tablet can be placed in any liquid and administered in an appropriate volume. Super saturated potassium iodide (SSKI) drops are available and can be administered if necessary; however, at their concentration of 1000 mg/mL, accurate dose titration for children would be difficult. The FDA has also released recent guidance for home preparation of KI for infants in children[26,27] (Tables 3 and 4). The FDA statement emphasizes the need to place KI in a tasty solution, because it is very salty; raspberry syrup best disguises the taste of KI. KI mixed with low-fat chocolate milk, orange juice, or flat soda (for example, cola) has an acceptable taste. Low-fat white milk and water do not hide the salty taste of KI.[26,27]

The protective effects of a dose of KI last approximately 24 hours. The need for more than a single dose will depend on several factors, including the ability to quickly evacuate the area of radiation contamination. If evacuation is not possible, KI should be given for the persistent presence of radioiodines (which have half-lives ranging from 5 hours to 7 days). Recommendations for continued dosing should be made by the Environmental Protection

TABLE 3. Guidelines for Home Preparation of KI Solution Using 130-mg Tablet[26]

- Put 1 130-mg KI tablet in a small bowl and grind into a fine powder with the back of a spoon. The powder should not have any large pieces.
- Add 4 tsp (20 mL) of water to the KI powder. Use a spoon to mix them together until the potassium iodide powder is dissolved in the water.
- Add 4 tsp (20 mL) of milk, juice, soda, or syrup (eg, raspberry) to the KI/water mixture. The resulting mixture is 16.25 mg of KI per teaspoon (5 mL)
- Age-based dosing guidelines:
  - Newborn through 1 mo of age: 1 tsp
  - 1 month through 3 y of age: 2 tsp
  - 4 years through 17 y of age: 4 tsp (if child weighs more than 70 kg, give 1 130-mg tablet)

How already prepared potassium iodide mixture should be stored:

Potassium iodide mixed with any of the recommended drinks will keep for up to 7 days in the refrigerator.

The FDA recommends that the potassium iodide drink mixtures be prepared fresh weekly; unused portions should be discarded.

TABLE 4. Guidelines for Home Preparation of KI Solution Using 65-mg Tablet[27]

- Put 1 65-mg KI tablet in a small bowl and grind into a fine powder with the back of a spoon. The powder should not have any large pieces.
- Add 4 tsp (20 mL) of water to the KI powder. Use a spoon to mix them together until the potassium iodide powder is dissolved in the water.
- Add 4 tsp (20 mL) of milk, juice, soda, or syrup (eg, raspberry) to the KI/water mixture. The resulting mixture is 8.125 mg of KI per teaspoon (5 mL)
- Age-based dosing guidelines:
  - Newborn through 1 mo of age: 2 tsp
  - 1 mo through 3 y of age: 4 tsp
  - 4 y through 17 y of age: 8 tsp or 1 65-mg tablet (if child weighs more than 70 kg, give 2 65-mg tablets)

How already prepared potassium iodide mixture should be stored:

Potassium iodide mixed with any of the recommended drinks will keep for up to 7 days in the refrigerator.

The FDA recommends that the potassium iodide drink mixtures be prepared fresh weekly; unused portions should be discarded.

Agency, the NRC, or other federal or state agencies that will be conducting environmental assessment. Radioactive dispersal devices generally would not contain radioiodines, so administering KI after detonation of a radioactive dispersal device would be inappropriate.

Other aspects of clinical care after radiation exposure are listed in Table 5 and include serial complete blood cell counts with close monitoring of absolute lymphocyte count, administration of antiemetics as needed, rigorous infection control, and aggressive treatment of infectious illnesses. Management of infection is the mainstay of therapy, because victims have significant immunosuppression; neutropenia and lymphopenia may last for several weeks.[15,19] Should a severe radiation exposure occur, other interventions to consider (although sufficient data are currently lacking) include administration of hematopoietic growth factors, (eg, granulocyte colony-stimulating factor) and HLA antigen typing for victims in whom the need for bone marrow transplantation is anticipated.[17] Available data suggest that granulocyte- and granulocyte-macrophage colony-stimulating factors should be administered within 24 to 72 hours of radiation exposure for optimal efficacy.[23]

Management of the psychologic harm to children after a radiation disaster requires that pediatricians provide advice to parents and supportive counseling to children and families.[28–31] Pediatricians should screen children closely for the presence of adjustment reactions and stress responses after a disaster has occurred. They should additionally assist parents in identifying the early signs of adjustment reactions, particularly in toddlers and other children who may have difficulty verbalizing their feelings. Finally, children should be referred for mental health services in a timely manner when behavioral disturbances are found.[32]

Other specific clinical recommendations are available from the Oak Ridge Institute for Science and Education,[18] from the Armed Forces Radiobiology Research Institute,[19] and in recent clinical reviews.[14,17]

LATE EFFECTS

Cancer

Among long-term injuries to children, carcinogenesis is most important. Studies suggest that radiation exposure during childhood is associated with a greater risk of cancer than is exposure at other ages.[4,13] For example, the risk of breast cancer is increased in women who are exposed to high levels of radiation as children, especially if the radiation exposure occurs before the pubertal development of breast tissue.[13,33–35] A peak in childhood leukemia occurred 5 to 6 years after the detonation of the nuclear bomb in Hiroshima and Nagasaki. There were 46 cases among those who were then younger

TABLE 5. Diagnostic Measures to Consider in Victims of Radiation Exposure

Test	Timing
Nasal swab to identify inhalation*	Immediately
Skin swabs to identify external contamination*	Immediately and at frequent intervals
Urine and stool analysis to identify internal contamination*	Immediately and at 24 h
Complete blood cell and platelet counts	Daily for 1 wk
Absolute lymphocyte count	Every 12 h for 3 d
HLA antigen subtyping	Before lymphocyte count decreases
Lymphocyte cytogenetics	Before lymphocyte count decreases

* A radiation safety officer or other authority should be consulted in all aspects of management.
Adapted from Jarrett DG. *Medical Management of Radiological Casualties.* Bethesda, MD: Armed Forces Radiobiology Research Institute; 1999

than 19 years of age (16 acute lymphocytic, 18 acute myelogenous, 10 chronic myelogenous, and 2 other). The excess cases diminished 16 years after exposure.[36]

Radiation-induced thyroid cancer in children has been well characterized. In the Chernobyl disaster, a cloud of radioactive elements including radioiodines was released. In the area of fallout in the Ukraine, 577 children and adolescents developed thyroid cancer between 1991 and 1997 (compared with 59 cases of thyroid cancer in the 5 years preceding the disaster). The number was greatest among those who were exposed at 5 years of age or younger. The latency period was short and the cancer was aggressive. In most cases, the radiation dose was 0.50 Gy or more.[37] In the United States, published data suggest that elevated rates of thyroid cancers and adenomas occurred among a cohort of children exposed to fallout from nuclear weapons tests in Nevada between 1951 and 1958.[38] Benign thyroid neoplasms are more common than thyroid cancer after radiation exposure; these can produce morbidity because of the possible need for surgery and lifelong medical follow-up.

Radiation-induced tumors can be benign or malignant and are histologically indistinguishable from the same cancers in the general population. The latency period for carcinogenesis after radiation exposure is typically 2 to 3 years for leukemia and 10 or more years for thyroid cancer and other solid tumors.[2,14,23] The latency period for thyroid cancer in children exposed to radioiodines after the Chernobyl disaster was shorter; an increase was observed beginning 4 years after the event.[9]

Psychologic Effects

One of the most common and disabling consequences of radiation exposure is the development of chronic fear and anxiety. More than 6 years after Chernobyl, the large populations exposed in the 2 areas of fallout had a high prevalence of distress and behavioral disorders; 35.8% of respondents had a psychiatric diagnosis as defined by the *Diagnostic and Statistical Manual of Mental Disorders, Third Edition*.[39] A significantly higher rate was found among mothers with children younger than 18 years of age.[8,23,40,41] In an 11-year follow-up study of mothers and their young children, there continued to be significant psychosocial morbidity, with significantly higher scores on measures of social isolation and negative life events.[42] Similarly, studies in Pennsylvania after the TMI incident found long-term behavioral disturbances in mothers of young children.[43,44] Local inhabitants performed worse on behavioral tasks, had a greater incidence of psychosomatic symptoms, and had higher concentrations of neuroendocrine stress hormones than did controls.[11] The Kemeny Commission, convened to investigate the consequences of the TMI disaster, concluded that mental stress would be the main effect of a nuclear reactor disaster.[11,45]

Studies of the Goiania disaster also demonstrated that stress and behavioral reactions can follow perceived exposure; those living in the area of radiation exposure and those unexposed had behavioral and cardiovascular-neuroendocrine effects that persisted for more than 3 years.[23] Emotional effects are even greater for those who witness injured or mortally wounded victims after a radiation disaster.[11] These behavioral consequences can disrupt interpersonal relationships, attitude, and social outlook, causing or contributing to chronic medical conditions including hypertension.[23] Psychobehavioral disturbances are further magnified when disasters are accompanied by the loss of a family home or lack of timely information.[8,46] Finally, disaster workers and health care professionals can be incapacitated by the emotional distress of a radiation disaster.[23] This distress has multiple origins, including the inability to enter contaminated areas to rescue victims and the difficulty in wearing personal protective equipment.

PREPARING FOR A RADIATION DISASTER

Clinical Issues

Local planning for a possible radiation disaster focuses on the creation of disaster management protocols, education of first responders and health care professionals, and acquisition of appropriate equipment and supplies. First responders should receive training in radiation consequence management, because they may unknowingly enter a radioactive area. Emergency physicians as well as pediatricians and other primary care physicians are potential medical responders to a radiation event and should also obtain training in this area.[18] Issues including emergency department configuration for the management of radiation-exposed individuals should be addressed.[18] Recent data indicate that most US hospitals remain unprepared for a nuclear event.[47]

In November 2001, the FDA issued updated guidance about KI use after exposure to radioactive iodine; KI is ineffective for other radionuclide exposures. According to these guidelines, the benefits of KI exceed its risks when a certain level of exposure has occurred (Table 2). KI efficacy is greatest when administered immediately before the exposure, at which time it can prevent 100% of radioiodine from reaching the thyroid. However, the efficacy of KI is 80%, 40%, and 7% when administered 2, 8, and 24 hours after exposure, respectively[48]; these rates are markedly lower in children who are iodine-deficient. KI appears to have little clinical value when administered 12 hours or more after exposure.

Currently, the NRC recommends that state and local governments consider providing KI to all citizens living within 10 miles of a nuclear power plant as a supplement to plans for evacuation and sheltering.[49] In December 2001, the NRC wrote to the 31 states that had or were located near 10 miles of a nuclear power plant, offering 2 KI pills for every person living within 10 miles of a plant.[50] If states and local governments adopt the plan to use KI, communities should consider storage of KI in schools and child care centers. Additionally, strategies that permit the rapid administration to large numbers of children (eg, an entire elementary school) should be developed. The appropriateness of KI distribution to all US families remains controversial.

Universal prescription of KI has not been recommended by the NRC or FDA because the risks of radioiodine exposure exist only in certain regions and because of the risk of inappropriate use. However, given its limitless shelf-life, low incidence of adverse effects,[9,24] and need for rapid administration, universal access should be considered. KI is available without a prescription at some pharmacies but is not yet widely available. KI may be purchased through the Internet; however, families should be cautioned against using the medication before consulting with authorities.[9] In April 2002, the FDA listed 2 products, Thyro-Block (MedPointe Inc, Somerset, NJ), and IOSAT (Anbex Inc, Palm Harbor, FL), which are approved for over-the-counter use as a thyroid-blocking agent in radiation emergencies.[25] In November 2002, the *Medical Letter of Drugs and Therapeutics* listed these and additionally listed ThyroSafe (Recip US, Honey Brook, PA) as an FDA-approved product.[51] IOSAT can be obtained at 866-283-3986 and through the Internet at www.nukepills.com; Thyro-Block can be obtained at 800-804-4147 and at www.nitro-pak.com; and Thyro-Safe can be obtained at 610-942-8972 and at www.thyrosafe.com.[51] KI also can be ordered from Anbex Inc at 727-784-3483 and at www.anbex.com.

Communities near a nuclear power plant should have access to KI as an adjunct to evacuation and sheltering. It is prudent for parents living within 10 miles of a nuclear reactor to keep KI in their homes. In addition, schools and child care centers located within a 10 mile radius of a nuclear power plant should have immediate access to KI. It is unclear, however, whether people within a larger radius should stockpile the drug. Although current recommendations call for those within a 10-mile radius to have access to KI, there have been recent concerns that a nuclear power plant mishap could discharge a radioactive cloud with far greater reach. In the Chernobyl disaster, changes in wind direction and rainfall resulted in an unevenly distributed deposition of radionuclides. The 3 most highly contaminated areas were the 20-mile zone surrounding the reactor; the Bryansk, Russia area and Gomel and Mogilev regions of Belarus (120 miles north-northeast of the reactor); and the Kaluga-Tula-Orel area of Russia (300 miles northeast of the reactor).[52]

As a result of these concerns, some have suggested that all people living within a 50-mile radius of a nuclear power plant should stockpile KI.[50] There have also been proposals for the stockpiling of KI by all those living within a 200-mile radius of a nuclear plant.[50] Because rapid and complete evacuation of a region is dependent on population density, a more cogent approach might be to vary the recommended KI distribution radius by population density. In population-dense regions, a 50-mile radius could be used, and areas with a lower population could adhere to the 10-mile radius recommendation.

The establishment of nuclear disaster response teams is also a part of community planning. Such teams should include mental health professionals who are trained to respond to the emotional and behavioral needs of children after a radiation event. Because children with psychologic trauma may be unable to verbalize their feelings, parents and pediatricians should be attentive to subtle signs of stress, anxiety, or depression.

Preparatory training exercises are also recommended. To date, involvement of pediatricians and mental health professionals in mock radiation disasters has been minimal. However, without these participants, mock disasters are likely to make unrealistic assumptions about the behavior of all victims, including children.[20] The inclusion of pediatricians and mental health specialists in planning will provide the opportunity to evaluate, improve, and enhance the response.

Public Health Actions

States and local governments have begun to develop strategies to protect their local population after a radiation release.[53] These include the establishment of threshold radiation concentrations that would require evacuation and educational campaigns for the public. All residents in at-risk areas should receive educational information and detailed emergency response plans.[53] Special plans should be made for children with disabilities.

Local hospitals also have a key role in the preparation for a radiation disaster. Policies of the Joint Commission on Accreditation of Healthcare Organizations require that health care facilities develop disaster management guidelines and that these guidelines be subject to twice-yearly drills. Because radiation events represent a unique catastrophe, hospitals should provide detailed guidance. Pediatricians may have the role of assisting hospitals in the development of plans for treating pediatric victims.

Schools and child care facilities should also be included in response plans, particularly if they are located within 10 miles of a nuclear power plant. School evacuation plans should be created and practiced. Many school districts have already been successful in creating algorithms for evacuation of children and their rapid reunification with parents.[54] School plans should consider the designation of an out-of-state relative or friend as a "family contact," because during a disaster, it is often easier to call long-distance than locally to find a family member. As with planning for all disasters, medical directives (eg, health care proxy) should be considered in the event the parent of an ill or injured child cannot be immediately contacted. Schools should have written plans that define locations within the school building or in nearby structures that would afford the best protection from a radiation cloud. School-based crisis-management teams that manage other events associated with psychologic trauma should be trained to respond to the consequences of a radiation disaster.

PREVENTION

Radioactive materials are used throughout the country, particularly in research and medical treatment. These radioisotopes are subject to theft or sabotage. For example, in 1996, a radiographer disappeared for approximately 2 weeks with a cache of radioactive iridium; in the same year, 2 radioactive cobalt sources were stolen from an abandoned industrial facility.[10] Many other confiscations of radioactive material have occurred.[55] These cases illustrate the ease with which radionuclides can be stolen and then used for the creation of a radioactive dispersal device. Stricter regulation and heightened surveillance of all high-dose radioactive materials is necessary to prevent such events from occurring.

The safety and vulnerability of nuclear power plants to terrorism has been questioned,[55,56] particularly since the events of September 11, 2001, when fuel-filled commercial airplanes were used as weapons.[14,57] Several acts of nuclear power plant sabotage have reportedly occurred in the past.[58] In addition to the risks associated with terrorist activity, the aging of US nuclear reactors has led to beliefs that a mishap is inevitable.[59] Concerned scientists and environmental advocates have long argued that nuclear power plants carry a risk of harm too great to justify their continued existence; calls for the shutdown of all US power plants have been building in recent years.[60] Currently, however, more than 20% of US electrical power is provided by nuclear power.[61] All sources of electrical energy have unwanted consequences or are currently unfeasible in terms of economic cost. Fossil fuel combustion releases carbon dioxide and other greenhouse gases as well as mercury, arsenic, and other pollutants; these emissions are associated with asthma, cancer, cardiovascular disease, and other chronic illnesses. Hydroelectric, solar, and wind energy, while clearly preferred, all have significant use limitations.[62] Until safer, sustainable sources of energy are available and with the need to decrease the use of fossil fuels, the immediate closure of existing nuclear plants may not be prudent.[62]

However, many have argued that future nuclear power plants should not be placed near heavily populated areas, and existing plants in densely populated regions should be decommissioned as quickly as possible. Additionally, the amount of nuclear wastes continues to grow; most are being stored in vulnerable, above-ground sites. Plans to create a large underground nuclear waste storage facility are nearly complete.[63] The proposed facility will house more than 77 000 tons of radioactive waste, delivered via an estimated 108 000 train and truck shipments over a 30-year period.[64] These plans, if implemented, will require intense security from terrorism, protection from crashes or other vehicular mishaps, and careful consideration of the potential for and effects of earthquakes in the vicinity.[65]

Through their daily practice, pediatricians can participate in the prevention of adverse effects of ionizing radiation. Radiation damage is incompletely repaired and adds throughout life.[66] Exposures from CT scans are high, compared with those from radiography, as noted in a joint statement of the Society for Pediatric Radiology and the National Cancer Institute.[67] The CT-scan dose to the brain is up to 600 times the dose to the chest from an anterior-posterior (AP) and lateral X-ray.[67] Children not only have greater susceptibility to radiogenic cancer[68] but also have longer life expectancies compared with adults, during which the latent period for cancer can be exceeded. The margin of safety for radiation effects diminishes as radiation exposures accumulate. Pediatricians can preserve the margin of safety by requesting radiologic procedures only when the benefits outweigh the risks and checking to ensure that CT operators are using settings appropriate for children.[69] Conservative use of diagnostic radiation procedures should decrease mortality and morbidity from the acute effects of a radiation disaster.

RECOMMENDATIONS FOR PEDIATRICIANS

1. Pediatricians should increase their knowledge about emergency medical aspects of radiation exposure.
2. Pediatricians should become familiar with local preparedness and evacuation protocols and work with public health agencies on their development.
3. Pediatricians should assist local schools and child care facilities in developing protocols to reunite children with their parents in the event a disaster.
4. All children at risk should receive KI before exposure, if possible, or immediately afterward. This will require that KI be available in homes located within 10 miles of a nuclear power plant. Child care facilities and schools within 10 miles of a nuclear power plant should plan to stockpile the agent. It may be prudent to consider stockpiling KI within a larger radius because of more distant windborne fallout, as occurred after Chernobyl; this will be determined by local and national public health authorities.
5. The risks and benefits of using KI should be discussed with parents. KI is available without a prescription, and families should be cautioned against using the medication before consulting with authorities.
6. Because radioiodines pass into breast milk, pediatricians should caution lactating mothers not to breastfeed their infants after the release of radioiodines, unless no alternative is available. The restriction is temporary, until public health authorities declare it safe to go back to breastfeeding. Public health authorities will also advise about the safe consumption of produce and milk after a radiation disaster.
7. The pediatrician should recognize and respond to the psychosocial consequences of disasters in children.[23,29,70]

RECOMMENDATIONS FOR GOVERNMENT

1. Pediatricians should be included in all aspects of planning for a radiation disaster. Disaster planning exercises should include pediatric casualties and victims with mock psychologic injuries.
2. Future sites for nuclear power facility construction should be selected to minimize the risk to populations. For existing power plants in popu-

lated regions, an accelerated timeline for decommissioning should be considered.
3. Guidelines for the population radius within which to recommend KI stockpiling should be developed; distribution plans should also be created.
4. The FDA should facilitate the development of a pediatric preparation of KI.
5. Plans should be developed for rapid communication with the public about evacuation versus sheltering, the safety of breast milk, and local food consumption.
6. Government planners should make mental health a high priority in the response plan for a radiation incident.

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APPENDIX: GLOSSARY OF TERMS

Types of Radiation

Ionizing radiation: a high-frequency, low-amplitude form of radiation that interacts significantly with biological systems.
Alpha particle (α-particle): a particle emitted from the nucleus of an atom. It contains 2 protons and 2 neutrons and is identical to the nucleus of a helium atom. Having a very large mass, α-particles have poor penetration. They pose little hazard after external exposure but can produce tissue injury when inhaled or ingested.
Beta particle (β-particle): a high-speed particle, identical to an electron, emitted from the nucleus of an atom.
Neutrons: a powerful but uncommon type of radiation, emitted only after a nuclear detonation. Neutrons are highly destructive, producing 10 times more tissue damage than γ-rays produce.
Gamma-rays (γ-rays): a form of ionizing radiation having no mass. Like visible light, γ-rays are made of photons. γ-Rays have significant penetrance and are the most important external radiation hazard after a radiation disaster.
X-rays: like γ-rays, x-rays have no mass; their energy is emitted from electrons, and γ-rays are emitted from nuclei.

Radiation Exposure Terms

Becquerel (Bq): the International System of Units (SI) measurement of radioactivity, defined as decay events per second. 1 Bq = 1 disintegration per second.
Curie (Ci): the traditional measure of radioactivity, as measured by radioactive decay. 1 Ci = 3.7×10^{10} disintegrations per second.
Radiation absorbed dose (rad): the energy deposited by any type of radiation to any type of tissue or material. 1 rad = 0.01 Gray
Roentgen equivalent man (rem): the unit of *human* exposure to radiation. 1 rem = 0.01 Sievert
Gray (Gy): the SI unit for the energy deposited by any type of radiation, in joules per kilogram. 1 Gy = 100 rad
Sievert (Sv): the SI unit for measurement of human exposure to radiation, in joules per kilogram. 1 Sv = 100 rem
Weighting or Quality Factor: a term that correlates rem with rad (rem = rad × quality factor), based on factors including the type of radiation. The quality factor for β-particles, γ-rays, and x-rays is 1; therefore, with exposure to these forms of radiation, rad = rem. The quality factor for α-particles is 20 (1 rad = 20 rem).

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