



# Pediatric Considerations Before, During, and After Radiological or Nuclear Emergencies

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Infants, children, and adolescents can be exposed unexpectedly to ionizing radiation from nuclear power plant events, improvised nuclear or radiologic dispersal device explosions, or inappropriate disposal of radiotherapy equipment. Children are likely to experience higher external and internal radiation exposure levels than adults because of their smaller body and organ size and other physiologic characteristics as well as their tendency to pick up contaminated items and consume contaminated milk or foodstuffs. This technical report accompanies the revision of the 2003 American Academy of Pediatrics policy statement on pediatric radiation emergencies by summarizing newer scientific data from studies of the Chernobyl and the Fukushima Daiichi nuclear power plant events, use of improvised radiologic dispersal devices, exposures from inappropriate disposal of radiotherapy equipment, and potential health effects from residential proximity to nuclear plants. Also included are recommendations from epidemiological studies and biokinetic models to address mitigation efforts. The report includes major emphases on acute radiation syndrome, acute and long-term psychological effects, cancer risks, and other late tissue reactions after low-to-high levels of radiation exposure. Results, along with public health and clinical implications, are described from studies of the Japanese atomic bomb survivors, nuclear plant accidents (eg, Three Mile Island, Chernobyl, and Fukushima), improper disposal of radiotherapy equipment in Goiania, Brazil, and residence in proximity to nuclear plants. Measures to reduce radiation exposure in the immediate aftermath of a radiologic or nuclear disaster are described, including the diagnosis and management of external and internal contamination, use of potassium iodide, and actions in relation to breastfeeding.

## abstract

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## BACKGROUND AND RATIONALE FOR UPDATE

Children can be exposed to environmental radiation as a result of nuclear power, fuels reprocessing, and weapons production plant (hereafter designated “nuclear plant”) events; from an improvised nuclear device or radiologic dispersal device; or from abandoned medical radiation equipment that could potentially result in substantial levels of radiation exposure and associated health effects. Because the radiation levels from these sources could lead to a radiation emergency, this term is used to refer to these types of exposures hereafter in this report. Children and their families are likely to be extremely anxious about such events and about residential proximity to nuclear plants (the latter being associated with very low or no radiation exposure) and may turn to their medical professional for advice. Health care professionals are concerned about these exposures because, in general, children are more sensitive to radiation and are more likely to develop the short-term and some of the long-term effects of radiation exposure. Children are likely to experience higher external and internal radiation exposure levels than adults because children are shorter and have smaller body diameters and organ sizes.<sup>1</sup> Children have a longer time to live and, thus, more time in which to develop adverse outcomes. In addition, children may ingest radioactive material from picking up contaminated items and putting hands in their mouths when crawling,<sup>2</sup> ingesting soil,<sup>3</sup> or consuming milk from cows feeding on contaminated pastures or feed.<sup>4</sup>

In a policy statement published in 2003,<sup>5</sup> the American Academy of Pediatrics (AAP) Council on Environmental Health summarized the history, features, and health effects associated with radiation emergencies in children and provided

recommendations for treating, mitigating, and preventing serious health effects in children. An update to the policy statement is needed that incorporates (1) new scientific knowledge from late-effects studies of the Chernobyl event, (2) lessons from the 2011 Fukushima Daiichi Japanese nuclear power plant event, (3) information pertinent to the use of improvised radiologic dispersal devices and the specter of nuclear detonation in heavily populated regions, (4) radiation exposures from the inappropriate disposal of radiotherapy equipment, (5) reports of potential health effects associated with radiation exposures of children living in proximity to nuclear plants, and (6) recommendations based on new knowledge from epidemiological studies and from biokinetic models to address mitigation efforts.

A number of AAP publications are related to the material in this technical report, including (1) “Medical Countermeasures for Children in Public Health Emergencies, Disasters, or Terrorism”<sup>6</sup>; (2) “Ensuring the Health of Children in Disasters”<sup>7</sup>; and (3) “Providing Psychosocial Support to Children and Families in the Aftermath of Disasters and Crises.”<sup>8</sup> This technical report presents detailed information that supports the recommendations of the accompanying policy statement.<sup>9</sup>

## TYPES OF RADIATION EMERGENCIES AND RELATED EXPOSURES

The description and findings from epidemiological studies of the most important types of radiation emergencies and related exposures are summarized in Table 1. Concern about health effects associated with radiation emergencies began with the atomic bombings in Hiroshima and Nagasaki in 1945 that killed more than 100 000 people and injured nearly as many. Concern about adverse health and genetic effects

led to long-term follow-up studies of mortality (established in 1950) and cancer incidence (begun in 1958) that continue to the present day and have yielded critically important data.<sup>10</sup>

Four major nuclear plant accidents have occurred: Windscale in Seascale, Cumbria, in the United Kingdom (1957); Three Mile Island in Pennsylvania (1979); Chernobyl in Ukraine (1986); and Fukushima Daiichi nuclear power plant in Fukushima Prefecture, Japan (2011).

Beginning in 1945, atmospheric nuclear testing was undertaken by the United States (New Mexico, Nevada, and the Marshall Islands), the Soviet Union (Kazakhstan), the United Kingdom (Australian territories and some Pacific Islands), France (French Polynesia), and China (Gobi Desert in Xinjiang Province) and resulted in 504 devices exploding at 13 sites. A 1963 treaty led to a limited test ban by the Soviet Union, the United States, and the United Kingdom, but atmospheric testing continued until 1974 by France and until 1980 by China.<sup>4</sup> Health studies have been focused on cancer risks in military participants and/or observers and on thyroid cancer and leukemia occurring among the general population living in proximity to the testing sites.<sup>19,24</sup>

Events involving abandoned medical radiation equipment have resulted in acute radiation sickness and deaths as well as contamination of thousands of people and homes.<sup>22</sup>

Since 1983, concerns about excess leukemia among children living in proximity to nuclear power, fuels reprocessing, and weapons-production facilities have led to epidemiological studies of more than 200 nuclear facilities in 10 countries.<sup>23</sup> Most of the studies reveal no association. Confounding cannot be ruled out in the few studies that have revealed an association, particularly because small

**TABLE 1** Characteristics of Physical Health Outcomes From Radiation Disasters and Related Events

Disaster or Event Category; Publication	Exposed Populations	Radiation Released	Population Studied	Radiation Levels	Health Outcomes
Atomic bombings, Hiroshima and Nagasaki, 1945 Preston et al <sup>11</sup>	Hiroshima, Nagasaki	Detonation at high altitudes produced minimal fallout; direct radiation was important only within 3 km	2452 in utero	0.005–3 Sv	Significant excess of all solid cancers was first observed after 5 decades of follow-up.
Preston et al <sup>11</sup>	Hiroshima, Nagasaki	Detonation at high altitudes produced minimal fallout; direct radiation was important only within 3 km	15 388 <6 y	0.005–3 Sv	Significant excess of all solid cancers after 5 decades of follow-up; risks were higher than those in utero at the time of the bombings.
Preston et al <sup>12</sup>	Hiroshima, Nagasaki	Detonation at high altitudes produced minimal fallout; direct radiation was important only within 3 km	30 000 children	0.005–3 Sv	Significant excess risks for cancers of most anatomic sites; risks were highest for those exposed at youngest ages; risks declined 17% per decade of age at exposure; excess cancer risks persist throughout life.
Nuclear plant accidents, 1957–2013 Cooper et al <sup>13</sup>	Windscale, 1957	750 TBq of radioactive materials were released, including 22 TBq of <sup>137</sup> Cs and 740 TBq of <sup>131</sup> I	No epidemiological study of children residing in proximity	NA	Risk projection assessment only, without validation; accident may have resulted in 240 excess cases of thyroid cancer.
Report of the President's Commission on the Three Mile Island accident <sup>14</sup>	Three Mile Island, 1979	The highest radiation doses were from krypton and xenon; iodine was released in barely measurable quantities	Dose data were not available separately for those exposed as children.	Doses were estimated to be about the same as natural background radiation exposure	No measurable differences between 3582 exposed (within 10 miles of Three Mile Island) versus 4000 unexposed pregnant women for prematurity, congenital abnormalities, hypothyroidism, neonatal deaths, or other factors. No excess leukemia or cancer was noted in entire exposed population or offspring.
Brenner et al <sup>15</sup>	Chernobyl, 1986	1760 PBq radioiodines, 85 PBq <sup>137</sup> Cs, 1150 PBq tellurium-132, 5200 PBq <sup>135</sup> Xe, and particulate radionuclides	12 514 people <18 y residually proximate in Ukraine at exposure; 65 incident thyroid cancers	<0.05–≥3 Gy	Incidence of thyroid cancer significantly increased twofold at 15–22 y; no downturn.
Harada et al <sup>16</sup>	Fukushima Daiichi nuclear accident, 2011	340–800 PBq released into the atmosphere as of 2014, with 80% falling into the Pacific Ocean	Epidemiological study under development	Measurements in 3 nearby locations ranged from 1.03 to 1.66 mSv/y from external radiation and 0.0058–0.019 mSv/y from internal radiation.	Risk projection suggests that lifetime increases in risk from solid cancer, leukemia, and breast cancer will be increased by 1.06%, 0.03%, and 0.28%, respectively.

**TABLE 1** Continued

Disaster or Event Category; Publication	Exposed Populations	Radiation Released	Population Studied	Radiation Levels	Health Outcomes
Aboveground nuclear tests, 1949–1980 Lyon et al <sup>17</sup>	Nevada test site	86 atmospheric tests during 1951–1962	2497 children ages 12–18 y	0–400+ mGy; mean = 120 mGy	Incidence of thyroiditis 20 y after baseline assessment was fivefold increased; too few thyroid cancers were present to estimate risks.
Simon et al <sup>18</sup>	Marshall Islands	66 atmospheric tests during 1946–1958	No epidemiological study, risk projection	Whole-body doses ranged from 5 to 2000 mGy; thyroid doses ranged from 12 to 7600 mGy.	Estimated that 1.6% of all cancers among Marshall Islands residents alive between 1948 and 1970 were attributable to the radiation from the testing
de Yathaire et al <sup>19</sup>	French Polynesia	41 atmospheric tests during 1966–1974	Case-control study: 229 thyroid cancer cases versus 373 controls	Thyroid doses ranged from 0 to 39 mGy for cases and 0–36 mGy for controls. Average dose to cases for those <15 y of age was 1.8 mGy.	Significant dose-response relationship observed; high excess risk of thyroid cancer with wide confidence intervals
Land et al <sup>20,21</sup>	Semipalatinsk	456 atmospheric tests during 1949–1989	Prevalence of ultrasound-detected thyroid nodules in 2376 people <21 y from nuclear tests, 1949–1962	Estimated doses, Gy External: range = 0–0.55, and mean = 0.056; internal: range = 0–3.1, and mean = 0.20	Significant dose response for thyroid nodules; risk was fivefold increase in male individuals, but only 27% (and nonsignificantly) higher in female individuals.
Inappropriately discarded radiation medical equipment International Atomic Energy Agency <sup>22</sup>	Goiânia, Brazil	Old radiotherapy source was stolen, dismantled, and handled by many people; contained <sup>137</sup> Cs	No systematic epidemiological study	Most had estimated doses of <0.5 Gy, but several had substantially higher doses up to 6 Gy.	4 people died, 112000 people were screened, 249 had significant radiation levels; 42 homes were decontaminated or destroyed.
Residence in proximity to nuclear plant, 1983–present Laurier et al <sup>23</sup>	Populations in proximity in United Kingdom, United States, France, Germany, and other countries	Studies of close to 200 geographic sites in proximity to nuclear plants in 10 countries; 25 multisite studies	Some variation, but generally leukemia in people <25 y (most studied younger ages)	Measured radiation levels were lower than levels from natural background radioactivity.	Some clusters were observed including in proximity to Sellafield and Dounreay nuclear reprocessing plants in the United Kingdom and in Elmarsch near Krümmel plant in Germany and perhaps Aldermaston and Burghfield (United Kingdom) and La Hague (France), but multisite studies reveal no increase in risk

<sup>137</sup>Xe, xenon-133; NA, not applicable; PB, petabecquerel; TB, terabecquerel.

increases in risk were observed with distance from sites for proposed nuclear power stations that were never built.<sup>25</sup>

## **CHARACTERISTICS, UNITS, SOURCES, AND BIOLOGICAL EFFECTS OF RADIATION EXPOSURE**

### **Terminology**

Ionizing radiation, a type of high-frequency energy that can produce adverse effects through damage to DNA and cells, includes electromagnetic (eg, radiographs and  $\gamma$ -rays, involving streams of photons or “packets” of energy) and particulate forms (eg, electrons, protons,  $\alpha$ -particles, neutrons, muons, and heavy-charged ions). Radionuclides (often referred to as radioactive isotopes) are atoms with unstable nuclei that release excess energy by the emission of  $\gamma$ -rays or  $\alpha$ - or  $\beta$ -particles when they undergo radioactive decay.<sup>26</sup>

### **Units**

Energy from radiation is measured in several types of units. The international system (Système International d’Unités [SI]) unit Gy (1 Gy = 100 rad) is the radiation absorbed dose. The SI unit Sv (1 Sv = 100 rem) takes into account a weighting or quality factor that is based on the relative biological effectiveness of doses from particulate radiation (eg, Sv = Gy  $\times$  relative biological effectiveness). The SI unit of activity for radiation emission of a radionuclide is Bq, which is defined as 1 atomic disintegration per second (for conversion, 1 Bq =  $1/3.7 \times 10^{10}$  Ci). The most important radionuclides and radioactive emissions associated with radiation emergencies are shown in Table 2.

### **Characteristics and Sources**

Children can be exposed to radiation emitted from sources that are external or internal to the body.

Exposure may occur to the whole body (eg, external radiation from natural background exposures or radiation emergencies) or may involve partial body exposure (eg, radiographs from medical radiography and most forms of radiotherapy). Sources of exposure may include natural background exposure (eg, radon, natural background  $\gamma$ -rays, cosmic rays) or manmade exposures (eg, radiographs from medical radiography, radionuclides administered in nuclear medicine procedures, and the radioactive materials used in nuclear power or weapons plants). Several key forms of ionizing radiation are encountered in radiation-related emergencies.  $\beta$ -particles are emitted from radionuclides that are created as by-products of nuclear reactors (such as radioactive iodines) or may be released from radionuclides used in medicine (such as xenon).  $\gamma$ -Rays are emitted from various radionuclides like isotopes of cesium and cobalt and after a nuclear detonation. Neutrons are mostly emitted after a nuclear detonation and are more effective at producing tissue damage than  $\gamma$ -rays. Other forms of radiation, such as  $\alpha$ -particles, which are emitted from radon or from polonium-210, have a shorter range.<sup>4</sup>

Children can become internally contaminated with radioactive material in a number of scenarios, such as the detonation of an improvised nuclear device (a device that incorporates radioactive materials designed to result in dispersal of radioactive material). Other examples include the release of radioactive material in the environment from a radiologic dispersal device (a bomb made from radioactive material combined with conventional explosives that is capable of spreading radioactive material over a wide area) or from a nuclear plant accident. The radioactive material may enter the body through

inhalation, by ingestion, or by blast injection into a wound. Dermal absorption is usually limited, except in cases of skin contamination with tritium. The clinical consequences of internal contamination depend on the type and amount of radioactive material that is taken up by the body and its chemical and physical (radioactive) properties.

### **Biological Effects**

Ionizing radiation may interact directly with target tissues or indirectly through the production of free radicals from its interaction with water molecules. Effects of radiation on cells differ depending on the cell’s rate of division and with the level of cell differentiation. Tissue sensitivity to radiation varies from highest to lowest as follows: lymphocytes, erythroblasts, spermatogonia, epidermal stem cells, and gastrointestinal stem cells. Other types of cells (muscle, bone, and nerve cells) are less sensitive to the effects of radiation. DNA appears to be the principal target for biological effects of radiation, including cell death, mutation, and carcinogenesis. If cells are irradiated with ionizing radiation, single-strand or double-strand DNA breaks or other DNA changes may occur. This can be followed by error-free DNA repair, but if the repair is incorrect, it can result in cell death, chromosomal instability, mutation, and/or carcinogenesis.<sup>26</sup> Indirect effects may occur through the production of free radicals in living tissue and nontargeted effects, such as release of cytokines and other products of inflammation.

## **EXAMPLES OF MEASURES TO REDUCE RADIATION EXPOSURES DURING AN EMERGENCY**

Below are examples of strategies to reduce exposure to radiation and associated health risks.



**TABLE 2** Radionuclides Potentially Released From a Radiation Disaster; Routes of Absorption and Treatments

Element, Symbol, Source	Type of Radiation; Half-life	Respiratory Absorption	Gastrointestinal Absorption	Primary Toxicity	Treatment
Americium <sup>241</sup> Am	α; 432 y	75%	Minimal	—	Calcium or zinc DTPA <sup>a</sup>
Californium <sup>252</sup> Cf	α, strong neutron emitter; 2.4 y	—	25% absorbed in liver	65% absorbed in bone; half deposited in skeleton and liver are gone in 50 and 20 y, respectively	Calcium or zinc DTPA
Carbon <sup>14</sup> C	Weak β emitter; 5730 y	Yes	Yes	Can cross placenta, becomes organically bound to developing cells and hence endangers fetuses	No treatment available
Cesium <sup>137</sup> Cs	β, γ; 30 y	Complete	Complete	—	Prussian blue <sup>a</sup>
Cobalt <sup>60</sup> Co	β, γ; 5.3 y	High	<5%	—	—
Iodine <sup>131</sup> I, <sup>125</sup> I	β, γ; 8 d, 60 d, respectively	High	High	—	KI <sup>a</sup> immediately before or within 4 h of exposure
Plutonium <sup>238/239</sup> Pu	α, radiographs; 24 400 y	High	Minimal	—	Calcium or zinc DTPA <sup>a</sup>
Strontium <sup>90</sup> Sr	β, γ; 28 y	Limited	Moderate	—	Aluminum hydroxide; calcium chloride suspension; calcium gluconate
Thallium <sup>201</sup> Tl	Potassium analog, when injected emits 80 keV radiographs; 73 h	—	—	—	Prussian blue
Tritium <sup>3</sup> H	Hydrogen isotope, decays with emission of low-energy electron; 10 d	—	—	Tritiated water is taken easily into the body by inhalation, ingestion, or transdermal absorption; instantaneously absorbed and mixes with body water	Force fluids; water diuresis
Uranium <sup>235</sup> U and radon daughters	α; 4.47 billion y	Inhalation can cause lung cancer	Ingestion can cause bone and liver cancer	—	Bicarbonate to alkalize the urine

Other important radionuclides in radioactive fallout that may contribute to internal dose and are not included in the table are as follows: iron-55 (<sup>55</sup>Fe), ruthenium-106 (<sup>106</sup>Ru), antimony-125 (<sup>125</sup>Sb), cerium-144 (<sup>144</sup>Ce), neptunium-239 (<sup>239</sup>Np), technetium-132 (<sup>132</sup>Te), barium-140 (<sup>140</sup>Ba), molybdenum-99 (<sup>99</sup>Mo), lanthanum-140 (<sup>140</sup>La), rhodium-105 (<sup>105</sup>Rh), promethium-149 (<sup>149</sup>Pm), praseodymium-143 (<sup>143</sup>Pr). Adapted from American Academy of Pediatrics Committee on Environmental Health. Radiation disasters and children. *Pediatrics*. 2003;111(6 pt 1):1455–1466. Adapted from Goans RE. *Medical Management of Radiological Casualties*. 4th ed. Bethesda, MD: Armed Forces Radiobiology Research Institute, Uniformed Services University of the Health Science; 2013.<sup>27</sup> <sup>3</sup>H, tritium-3; <sup>14</sup>C, carbon-14; <sup>60</sup>Co, cobalt-60; <sup>90</sup>Sr, strontium-90; <sup>125</sup>I, iodine-125; <sup>201</sup>Tl, thallium-201; <sup>235</sup>U, uranium-235; <sup>239</sup>PU, plutonium-238; <sup>239</sup>Pu, plutonium-239; <sup>241</sup>Am, americium-241; <sup>252</sup>Cf, californium-252; DFOA, deferoxamine; DMSA, dimercaptosuccinic acid; DTPA, diethylenetriaminepentaacetic acid; EDTA, edetic acid (ethylene-dinitrillo tetraacetic acid); NAC, N-acetyl cysteine. —, not applicable.

<sup>a</sup> Approved by the FDA for this indication.

### Measures to Reduce Contamination Immediately After an Incident

Guidance to individuals and professionals on measures to reduce contamination in the immediate aftermath of a radiologic or nuclear disaster is provided by the US Department of Health and Human Services<sup>28,29</sup> and the National Council on Radiation Protection and Measurements.<sup>30</sup> The immediate measures, summarized in Table 3, include specific actions to be undertaken

by children and parents to reduce external and internal contamination according to the person's location at the time of the emergency. More detailed information on many different aspects of responding to a nuclear event was published in 2010 by a federal interagency expert committee led by the Executive Office of the President.<sup>31</sup> Information in the document produced by the Federal Interagency Committee addresses such topics as identifying an expanded zone for management of activities, selecting

appropriate radiation detection devices, decontaminating critical infrastructure, conducting waste management, and many other key elements.

### Potassium Iodide

In the event that radioactive iodine is released into the environment, potassium iodide (KI) is a supplementary or secondary protective measure. The primary protection is sheltering in place or evacuation (as instructed by local public health officials) to prevent

**TABLE 3** Guidance to Parents on Individual Measures Immediately After a Radiation Emergency

Location or Topic	Actions to Be Taken
If outside or close to the location of the incident	Cover nose and mouth to reduce particulate exposures Do not touch objects thrown off by incident or dust Quickly go to nearest intact building with thick walls Once inside, take off outer clothes, place in a sealed bag, and place bag where others will not touch Shower and wash body and hair with soap and water Turn on radio and/or television for further instructions
If inside building	If building is not intact (ie, there are broken windows or walls), go to the nearest intact building Shut all windows, doors, and fireplace dampers Turn off all fans and heating and air conditioning units Turn on radio and/or television for further instructions
If in car	Close windows and vents and turn off heat and air conditioner Cover nose and mouth with a cloth If you cannot get to home or another intact building safely, stay in car and park in a safe place Turn off engine Turn on radio and listen for instructions Stay in car until told it is safe to get back on the road
Children and family	If with children and family, stay together If children are in another building or school, children should stay there, and parents should not travel to children until told it is safe to travel Children should stay in emergency shelter at school
Pets	Bring pets inside an intact building Wash pets with soap and water
Food and water	Do not consume any food or water out in the open air Food inside cans and sealed containers is safe, but food outside of cans and/or containers should be washed to remove dust Obtain guidance from authorities about other food and/or water

exposure in the first place. Guidance to federal agencies and state and local governments on safe and effective use of KI is provided by the US Food and Drug Administration (FDA).<sup>32</sup> The adoption and implementation of the recommendations are at the discretion of the state and local governments responsible for developing regional emergency response plans related to radiation emergencies. KI has been well established to block thyroid radioiodine uptake and is effective in reducing the risk of development of thyroid cancer in individuals and populations at risk after inhalation or ingestion of radioiodines.<sup>32,33</sup> The mechanism of action involves KI saturating the thyroid gland with nonradioactive iodine, thereby preventing uptake of the radioiodines, which are then excreted in urine. KI only prevents the uptake of radioiodines not the uptake of other radionuclides and is, therefore, not a general radioprotective agent. The FDA prioritizes treatment with KI on the basis of age, focusing on

infants, children, and pregnant and breastfeeding women, because they are at the highest risk of developing thyroid cancer. Treatment should be commenced immediately before or during the passage of a radioactive cloud in an event in which radioiodines are released, although treatment may still have a substantial protective effect even if 3 or 4 hours have passed. If the release of radioiodines and secondary exposure is protracted, then even delayed administration may result in benefits.

Shown in Table 4 are the threshold thyroid radioactive exposures and recommended doses of KI for different risk groups. At the time of the preparation of this document, there are 5 FDA-approved over-the-counter KI products:

- iOSAT tablets (65 and 130 mg; Anbex, Inc, Williamsburg, VA; [www.anbex.com](http://www.anbex.com))<sup>34</sup>;
- Thyrosafe tablets (65 mg; Recipharm, Jordbro, Sweden; [www.thyrosafe.com](http://www.thyrosafe.com))<sup>35</sup>;

- Thyroshield solution (65 mg/mL; Arco Pharmaceuticals, LLC, St Louis, MO; [www.thyroshield.com](http://www.thyroshield.com))<sup>36</sup>; and
- KI oral solution (65 mg/mL; Mission Pharmacal, San Antonio, TX).

KI provides protection for approximately 24 hours and should be given daily until the risk of exposure no longer exists. Pregnant women and neonates should not receive repeated doses of KI, because it has the potential to suppress thyroid function in the fetus and neonate (they must be prioritized for other protective measures, such as evacuation). The benefits of KI treatment to reduce the risk of thyroid cancer outweigh risks of transient hypothyroidism. However, given the potential sequelae of transient hypothyroidism for intellectual development, the FDA recommends that neonates treated with 1 dose or more of KI be monitored for this effect by measurement of thyroid-stimulating

**TABLE 4** Guidance on Use of KI

Age Group	Predicted Thyroid Gland Exposure, mGy	KI Dose, mg	No. or Fraction of 130-mg Tablets	No. or Fraction of 65-mg Tablets	Milliliters of Oral Solution, 65 mg/mL
>40 y	≥5000	130	1	2	2
18–40 y	≥100	130	1	2	2
Pregnant or lactating women	≥50	130	1	2	2
12–18 y <sup>a</sup>	≥50	65	0.5	1	1
3–12 y	≥50	65	0.5	1	1
1 mo–3 y	≥50	32	Use KI oral solution <sup>b</sup>	0.5	0.5
0–1 mo	≥50	16	Use KI oral solution <sup>b</sup>	Use KI oral solution <sup>b</sup>	0.25

<sup>a</sup> Adolescents approaching adult size (≥150 lb) should receive the full adult dose (130 mg).

<sup>b</sup> KI oral solution is supplied in 1-oz (30-mL) bottles with a dropper marked for 1-, 0.5-, and 0.25-mL dosing. Each milliliter contains 65 mg of KI iodide.

hormone and be treated with thyroid hormone therapy if hypothyroidism occurs.<sup>37–39</sup> Allergy to seafood, radiocontrast media, and povidone-iodine preparations should not be considered iodine allergy and are not a contraindication to the administration of KI. People with true iodine sensitivity should avoid KI, as should individuals with dermatitis herpetiformis and hypocomplementemic vasculitis, both rare conditions associated with increased risk of iodine hypersensitivity. People with Graves' disease and autoimmune thyroiditis should be treated with caution, especially if treatment extends beyond a few days. Adverse effects of KI may include skin rashes that can be severe (iododerma), swelling of salivary glands, and iodism (metallic taste, burning mouth and throat, sore teeth and gums, upper respiratory congestion, and occasionally gastrointestinal symptoms and diarrhea). Although KI is available over the counter, people should check with their doctors if there are any health concerns.<sup>32</sup>

### Measures Related to Breastfeeding

Data are limited on quantitative estimates of human milk activity from iodine-131 (<sup>131</sup>I) administered for nuclear medicine diagnostic or therapeutic procedures and from radionuclides resulting from radiation emergencies. Estimates based on biokinetic and other modeling data suggest that internal contamination from such sources could reach

substantial concentrations in human milk and result in significant radiation exposures to nursing children.<sup>40–43</sup> Higher levels of <sup>131</sup>I may be transferred to infants from breastfeeding than to the fetus from intake of the pregnant mother.<sup>44,45</sup> When the risk of exposure to radioactive iodine is temporary, mothers who are at risk for becoming internally contaminated can continue to breastfeed on the first day of exposure if appropriate doses of KI are administered to her and to the infant within 4 hours of the contamination. If not, the mother and infant should then be prioritized to receive other protective measures like evacuation.

According to the Centers for Disease Control and Prevention, women who are breastfeeding should take only 1 dose of KI if they have been internally contaminated with (or are likely to be internally contaminated with) radioactive iodine.<sup>46</sup> They should be prioritized to receive other protective action measures (<https://emergency.cdc.gov/radiation/ki.asp>). If the situation is such that the exposure to radioactive iodine is prolonged and more than 1 dose of KI is indicated for the mother and the infant, then breastfeeding must be temporarily suspended because of the risks associated with KI therapy in infants and neonates.<sup>47</sup> Mothers must be supported to express their milk to maintain their milk supply until the infant can resume breastfeeding. Safe human milk (that was pumped

and stored before the exposure) or ready-to-feed infant formula, to avoid potentially contaminated tap water, should be provided as a temporary solution. Breastfeeding can resume once public health officials indicate that it is safe.

If the mother's internal contamination with radioactive iodine is high or if repeat doses of KI to the infant are necessary (because of lack of availability of noncontaminated food sources), the infant should be evaluated for secondary hypothyroidism that could have resulted from the repeat dosing of KI.<sup>48</sup>

As a general measure, the mother should wash the nipple and breast thoroughly with soap and warm water and gently wipe around and away from the infant's mouth before breastfeeding.

Again, as noted above, it is important to reiterate that KI will not be protective if the exposure has been to radionuclides other than the radioiodines. Many radiation events will be a mix of radionuclides and/or not contain radioactive iodine. Public health officials will provide breastfeeding guidance after considering the risks and benefits that are particular to the specific event and radionuclides.

### DIAGNOSIS AND MANAGEMENT OF CONTAMINATION

The Radiation Emergency Medical Management Web site



(<https://www.remm.nlm.gov/>) provides a wealth of information on management of radiologic emergency incidents for both clinicians and managers. The Radiation Injury Treatment Network is another important resource (<https://ritn.net/default.aspx>). Pediatric patients and their accompanying family members who may have been contaminated from fallout and related radionuclides from radiation emergency events should be referred (or redirected if they appear at a pediatric practice) to hospital emergency departments with staff trained in decontamination, evaluation, and treatment measures for acute radiation syndrome (ARS), associated injuries, and related problems in patients, as well as protective measures for staff.

### External Contamination

Initial efforts to manage external contamination of parents and children at the community level are described in previous sections of this report and in Table 3. If parents and children have not removed and bagged clothing in sealed plastic bags and showered with soap and water before arriving at a central location or medical facility, they should do so.

### Internal Contamination

The diagnosis of internal contamination can be made by direct measurement of radiation emissions by using an external detector for radionuclides that decay by emitting  $\gamma$ -rays, such as  $^{131}\text{I}$  and cesium-137 ( $^{137}\text{Cs}$ ). Alternatively, analysis of urine or feces can be used to detect the radionuclides inside the body for radionuclides that do not emit  $\gamma$ -rays, such as polonium-210 and strontium-90. Performing these measurements in children will be more challenging than adults because of different body sizes that affect the radiation detector instrument calibration and because of greater difficulty in obtaining urine or fecal samples.

**TABLE 5** Guidance to Professionals on Drugs Available for the Treatment of Internal Contamination

Medical Countermeasure	Indication	Comment
Prussian blue	Enhances the fecal elimination of radioactive cesium or thallium by interrupting their enterohepatic circulation	Considered safe in children because it is not absorbed into the body. Not approved for ages <2 y. Use preemergency use authorization for ages 6 mo–2 y. Causes constipation and blue feces.
Pentetate calcium trisodium	Enhances the renal elimination of plutonium, americium, and curium	Approved in children. If >1 dose is needed, the zinc form is preferred.
Pentetate zinc trisodium	Enhances the renal elimination of plutonium, americium, and curium	Approved in children.
KI	Saturates the thyroid with stable iodine, which prevents the uptake of radioiodine.	See Table 3 and text.

Once the amount of radioactive material inside the body is estimated, it is compared with the corresponding radionuclide-specific Clinical Decision Guide.<sup>30</sup> The Clinical Decision Guide is meant to assist clinicians in determining whether the level of internal radionuclides is clinically significant. If the amount of radionuclide measured inside the body is greater than or equal to the corresponding Clinical Decision Guide, further medical management is warranted.<sup>49</sup> For radionuclides other than the isotopes of iodine, the Clinical Decision Guide values for children are 20% of those for adults because of their increased radiosensitivity.<sup>50</sup>

The medical management of patients with internal contamination consists primarily of supportive care and long-term monitoring for cancer and other health outcomes. Additional management strategies attempt to decrease the radiation dose received over the lifetime of the patient by enhancing the elimination of the radionuclide through diuresis or chelation therapy or by preventing uptake into the target organ. Specific drug therapies are available for a limited number of radionuclides and are listed in Table 5. The Centers for Disease Control and Prevention has developed an application to

assist clinicians in assessing and managing internal contamination. This tool, the Internal Contamination Clinical Reference application, can be downloaded to a mobile device free of charge at <http://emergency.cdc.gov/radiation/iccr.asp>.<sup>51</sup> It would be prudent to download and print this information in hard copy and arrange to keep the material easily available before a radiologic emergency, when communication problems may make it difficult to do so.

Many of the drugs and equipment specifically for use in disasters of all types, including nuclear and radiation disasters, are not used for other purposes and are therefore not routinely stocked in hospitals, pharmacies, or physician offices. The US government has created the Strategic National Stockpile, a national repository of antibiotics, vaccines, chemical antidotes, antitoxins, and other critical medical equipment and supplies. Material can be shipped to locations of need on short notice. Some individual states, particularly those with nuclear reactors, may have their own stocks of KI.

### HEALTH OUTCOMES

Some mental health effects of a radiation event may begin as soon

as the public becomes aware of the event; other mental health effects will be delayed. Physical health effects after radiation exposure include short-term effects that appear within days to months after radiation exposure and long-term effects that generally appear 18 months to many years later. The intervals between first exposure and long-term effects may be decades in length.<sup>10</sup> The types and severity of short-term effects are related in part to the level of exposure and the tissues exposed. In general, children are more sensitive to radiation and are more likely to develop both the short-term and some of the long-term effects of radiation exposure.

Mental health effects have long been known to be a major clinical problem associated with most types of radiation and other types of disasters.<sup>8,52</sup> Psychological effects potentially include anxiety; depression; fear; somatic complaints; and social, thought, and behavioral problems and other elements of posttraumatic stress disorder. Overall, the excess adverse psychological effects attributable to natural and manmade disasters is approximately 20% after the first 12 months.<sup>53</sup> Radiation-related disasters are of particular concern because of the intangible nature of radiation exposure, lack of information about the actual level of radiation exposure to individuals in the exposed population, conflicting reports about the details of the event by authorities and the media, widespread rumors about adverse effects on humans and animals, a tendency to attribute all subsequent short- and long-term health problems to radiation exposure, fears about health effects in future generations, nonsystematic health monitoring after the event, and social and economic disruptions.<sup>52</sup> Risk factors for adults that are associated with mental health consequences include the severity of the disaster;

postdisaster circumstances, such as adequacy of emotional support and access to professional interventions; and personal characteristics that increase susceptibility, including being female, having young children, and having previous psychiatric problems.<sup>53</sup> Long-standing research on the psychological effects of radiation disasters has been focused primarily on adults and has revealed acute as well as long-term anxiety, depressive symptoms, and somatic symptoms, particularly in mothers of young children.<sup>54</sup> Although short- and long-term effects on psychological functioning, emotional adjustment, and developmental trajectory of children subsequent to nonradiation disasters have been studied extensively,<sup>8,55</sup> mental health effects in children exposed to radiation disasters were not evaluated in methodologically rigorous longitudinal epidemiological studies until after the Three Mile Island<sup>54</sup> and Chernobyl accidents,<sup>53</sup> as described in more detail later in this report.

### Short-term Outcomes

#### ARS

ARS is an acute illness caused by irradiation of the whole or a large part of the body by a high dose of penetrating radiation over a short period of time (usually a few minutes). The time course of ARS can be divided into 4 nondiscrete phases: prodrome (occurring within minutes to hours of the radiation exposure and characterized by nausea, vomiting, fever, diarrhea, and fatigue); a latent phase (beginning a few hours after the exposure and lasting up to 2–5 weeks, during which patients may feel well but adverse effects occur at the tissue level); a manifest illness stage (potentially beginning as soon as a few hours after the exposure and lasting up to a few months); and recovery (beginning a few weeks after the event and lasting up to

2 years) or death.<sup>56</sup> ARS may also be conceptualized as a clinical continuum of manifestations that encompass multiple organs or systems and feature an important role for inflammation. This clinical continuum encompasses multiorgan injury, multiorgan dysfunction syndrome, and multiorgan failure, the latter being irreversible.<sup>57</sup> Treatments for emesis include ondansetron (approved for children of all ages) or granisetron (approved for children 2 years and older); bone marrow depression is treated with colony-stimulating factors like filgrastim, sargramostim, and pegfilgrastim.<sup>58</sup> These drugs are available, in some cases in limited quantities, in the Strategic National Stockpile.

#### *Symptoms, Outcomes, and Exposure Level*

The type, severity, and rate of appearance of clinical symptoms depend on the radiation dose received and the part of the body exposed. The larger the radiation dose absorbed by the body above the levels at which clinical symptoms are manifest, the more compressed the timeline of these phases and the more severe the clinical manifestation. The threshold whole-body dose for developing clinically apparent ARS is 1 Gy, although children may have a lower threshold than adults (Table 6). At whole-body doses of approximately 4.5 Gy, approximately 50% to 60% of exposed untreated patients will die. At doses of 8 Gy or more, virtually no patients will survive.

A patient's survival will depend on the dose of radiation received, the presence of other injuries (eg, trauma and burns), and comorbid medical conditions. During a mass-casualty incident, limited treatment resources will be allocated to patients who have survivable injuries, whereas others will be triaged for palliative care, highlighting the importance

of determining the radiation dose received by a patient. This dose can be estimated by using time to emesis and absolute lymphocyte counts based on data in adults. The Radiation Emergency Medical Management Web site provides tools to estimate radiation dose<sup>64</sup> Using the history and physical examination in addition to these estimation tools, health care providers can identify patients who are likely to develop the potentially survivable form of the ARS and therefore benefit from available medical countermeasures (Table 7).

### Short- and Long-term Effects: Mental Health Conditions

As noted previously, a major clinical problem associated with most types of radiation disasters is occurrence of mental health effects, including depression, anxiety, posttraumatic stress disorder, and medically unexplained somatic symptoms.<sup>67</sup> These problems may affect populations for many years after the event. As 1 example, long-term psychological effects have been documented among atomic bomb survivors.<sup>68–70</sup> Another example is the twofold increased lifetime depression rates among women living in proximity to Chernobyl

**TABLE 6** Clinical Effects in Relation to Whole-body Radiation Dose

Clinical Effect	Whole-body Dose, Gy
Threshold for developing clinically apparent ARS	1 (children may have a lower threshold than adults)
LD <sub>50/60</sub> without significant medical therapy <sup>59–63</sup> ( <a href="http://www.remm.nlm.gov/LD50-60.htm">http://www.remm.nlm.gov/LD50-60.htm</a> )	~4.5
LD <sub>100</sub>	8
Hematopoietic syndrome	2–6
Gastrointestinal syndrome	6–10
Cerebrovascular syndrome	>20
Cutaneous syndrome	>2 (to the skin)

LD<sub>50/60</sub>, lethal dose that will kill 50% of the exposed population within 60 days; LD<sub>100</sub>, lethal dose, 100%.

compared with the general population of women in Ukraine.<sup>71</sup> In both the Three Mile Island and Chernobyl (Ukraine) accidents, mothers of young children were 3 times as likely as women without young children to describe their health as “fair” or “poor,” which the investigators observed to be notable, given the differences in the levels of radiation exposure, evacuation, culture, and postdisaster sociopolitical environment.<sup>67</sup> The President’s Commission review of the health outcomes associated with the Three Mile Island accident concluded that the greatest public health problem was mental health,<sup>14</sup> similar to the conclusion of the Chernobyl Forum 20 years after the Chernobyl accident.<sup>72</sup> Psychosocial issues are addressed in much more

detail in a separate AAP clinical report titled “Providing Psychosocial Support to Children and Families in the Aftermath of Disasters and Crises.”<sup>78</sup>

### Long-term Effects: Cancer and Related Conditions

Several tissues (eg, thyroid, bone marrow, breast, and brain) are more sensitive to radiation in children than in adults, and children are at higher risk of radiation-related cancers of these tissues.<sup>73</sup> Other tissues do not appear to be more sensitive in children than in adults (eg, lung and bladder). Table 1 lists the key types of radiation emergencies considered, the affected populations, exposure information, whether a risk projection or epidemiological study was conducted, and key physical health outcomes.

**TABLE 7** Medical Countermeasures for Treating the Hematopoietic Subsyndrome of ARS

Medical Countermeasure	Indication	Comment
Granulocyte colony-stimulating factor (filgrastim and pegfilgrastim)	Neutropenia	Approved for use in adults and children.
Granulocyte-macrophage colony-stimulating factor (sargramostim)	Neutropenia	The liquid formulations containing benzyl alcohol or lyophilized formulations reconstituted with bacteriostatic water for injection, USP (0.9% benzyl alcohol), should not be administered to neonates and young infants.
Antibacterials	Neutropenia	Follow guidelines provided by professional societies (eg, Infectious Diseases Society of America and the American Society of Clinical Oncology <sup>65,66</sup> ).
Antivirals	Neutropenia	Follow guidelines provided by professional societies (eg, Infectious Diseases Society of America and the American Society of Clinical Oncology <sup>65,66</sup> ).
Antifungals	Neutropenia	Follow guidelines provided by professional societies (eg, Infectious Diseases Society of America and the American Society of Clinical Oncology <sup>65,66</sup> ).
Platelets	Thrombocytopenia	Irradiated and leukocyte reduced.
Packed red blood cells	Anemia	Irradiated and leukocyte reduced.
Stem cell transplant	Failure to respond to other therapies Absence of significant combined injuries or comorbid conditions	Contact the Radiation Injury Treatment Network ( <a href="https://ritn.net/default.aspx">https://ritn.net/default.aspx</a> )

USP, US Pharmacopeia.

### *Japanese Atomic Bomb Survivors: Life Span Study*

Much of our understanding of health effects from radiation disasters and emergencies is based on results of long-term follow-up of the survivors of the bombings in 1945 of Hiroshima and Nagasaki. The populations in these 2 cities each experienced a single high-dose-rate external radiation exposure.<sup>10</sup> The Life Span Study includes mortality follow-up since 1950 and cancer incidence follow-up since 1958 of 120 000 survivors, including approximately 30 000 children. The wide dose range (<0.005 Gy to 2–4 Gy; mean dose = 0.2 Gy), broad variation in age at exposure, and long-term follow-up has led to several key results (see Table 1). First, the radiation-related risks of solid cancers, and to a lesser extent the leukemias, except for acute myeloid leukemia, has persisted for more than 5 decades after exposure and may persist during the entire lifetime. Second, there is evidence of a linear dose response for all solid tumors combined, including a statistically significant dose response for survivors with cumulative estimated doses under 0.15 Gy. Significant radiation-associated excess risks were observed for most, but not all, specific types of solid cancers and for all types of leukemia except chronic lymphocytic leukemia, although the level of the excess relative risks per Gy and the excess absolute rates varied according to organ or tissue and by age at exposure. Third, the relative and absolute patterns of occurrence of solid tumors have been shown to be strongly modified by age at exposure, with children and adolescents demonstrating the highest risks.<sup>10</sup>

### *Japanese Atomic Bomb Survivors: In Utero Study*

The solid cancer incidence among atomic bomb survivors who were in utero at the time of the bombings (based on 94 incident cancers) was compared with risks among survivors exposed postnatally at

younger than 6 years (based on 649 incident cancers) and followed-up during 1958–1999. The excess relative risks at 50 years of age for a given dose was substantially higher for those exposed postnatally than for those exposed in utero. Excess absolute rates were markedly higher for a given attained age among those exposed in early childhood compared with a substantially lower increase for a given attained age among those exposed in utero (see Table 1).<sup>11</sup> Researchers of this study could not, however, provide cancer incidence risk estimates during childhood in the absence of complete cancer incidence data during 1945–1957 (the period after bombings but before the establishment of population-based cancer registries in Hiroshima and Nagasaki).

### *Nuclear Plant Accidents: Windscale, Three Mile Island, Chernobyl, Fukushima*

No epidemiological studies were conducted in the population residentially proximate to the Windscale nuclear plant after the accident. An investigation of cancer incidence in the population living in proximity to the Three Mile Island facility revealed no association for childhood cancers overall; an increased risk for childhood leukemia was based on only 4 cases, but incidence rates were low compared with regional and national rates.<sup>74</sup>

After the release of radioactivity from the Fukushima Daiichi nuclear power plant in March 2011 resulting from the Great East Japan Earthquake and tsunami, an effort was undertaken to estimate internal radiation levels, but information is limited because of initial organizational difficulties, high natural background radiation, and contamination of radiation measuring devices.<sup>75</sup> Direct measurements in a small number of early responders and evacuees who stayed in Fukushima for several days after the accident revealed low

maximum effective doses and thyroid equivalent doses. A large thyroid disease clinical ultrasonographic screening of approximately 300 000 residents 18 years or younger residing in the Fukushima Prefecture was conducted during 2011–2014.<sup>76</sup> The investigators reported a 50-fold excess incidence rate ratio when compared with the Japanese national thyroid cancer incidence for people of the same age. Despite the absence of individual organ radiation doses, the investigators indicated that the findings suggested a notable increase in thyroid cancer incidence attributable to the accident. However, many other radiation experts have concluded that this screening program identified the thyroid cancer incidence rates expected after screening. Other criticisms of the conclusions included the use of an inappropriate external comparison of a screened population with national rates not based on screening; absence of a statistical difference of the internal comparisons among the low, intermediate, and highly contaminated areas within the Fukushima Prefecture; low measured thyroid radiation levels that are inconsistent with the high risk estimates reported; lack of broad-based individual thyroid organ measurements; and the ecologic nature of the screening study (eg, no individual thyroid radiation doses were reported, so it is unclear whether thyroid cancer cases had higher radiation exposures than noncases).<sup>77–79</sup>

Approximately 5% to 7% of children from the Fukushima Prefecture who participated in the mental health surveys (participation rates ranging from 55% to 66%) required immediate support and counseling.<sup>80</sup>

Compared with other nuclear plant accidents, the dose estimation effort and assessment of long-term health risks conducted after the Chernobyl accident have been much more comprehensive. From follow-up



studies of children and adolescents exposed to radioiodines in the fallout from Chernobyl, studies have consistently revealed sizeable dose-related increases in thyroid cancer, with risks greatest in those youngest at exposure and potentially among those with a deficiency of stable iodine levels.<sup>81</sup> Studies of pediatric leukemia in Ukraine, Belarus, and Russia after the Chernobyl accident have shown inconsistent results, but there was no evidence of excess leukemia in European countries after the accident.<sup>82</sup>

#### *Aboveground Nuclear Testing*

Thyroid cancer and other thyroid diseases have been evaluated in children and adolescents exposed to the fallout from aboveground testing in Nevada, the Marshall Islands, French Polynesia, and Kazakhstan. Most of these studies have revealed dose-response increases in the risk of these outcomes (Table 1).<sup>17–20</sup>

#### *Inappropriately Discarded Medical Radiation Equipment*

For the most part, there has been little systematic study and no long-term follow-up of populations exposed to radiation from events involving abandoned medical radiation equipment. The incident in Goiania, Brazil, has been described in detail (see Table 1). An old <sup>137</sup>Cs teletherapy source stolen from an abandoned hospital in 1987 in Goiania, Brazil, was dismantled, and many people handled the pieces. As a result of this event, among the 112 000 people that were monitored, 4 people died, 1 person had an arm amputated, 249 people were contaminated with <sup>137</sup>Cs, and 42 homes had to be decontaminated or destroyed.<sup>22</sup>

#### *Residential Proximity to Nuclear Plants*

Extensive investigations quantifying risks of childhood leukemia in proximity to approximately 200

nuclear power plants and weapons facilities in 10 countries have mostly shown no increase in risk, with a small number of exceptions.<sup>23,25</sup> Pediatric leukemia clusters have been identified in proximity to Sellafield and Dounreay nuclear fuels reprocessing plants in the United Kingdom, in Elmarsch near the Krümmel plant in Germany, and perhaps in proximity to the Aldermaston and Burghfield weapons production plants in the United Kingdom and the La Hague nuclear power plant in France.<sup>23</sup> There is no clear evidence of increased risk based on multisite studies.<sup>23</sup> Alternate hypotheses used to explain these childhood leukemia clusters have been proposed, but to date there is no confirmatory evidence that can be used to support these hypotheses. The limitations of many of the studies conducted to date include inadequate study designs, residence information restricted to the location at the diagnosis of childhood leukemia and absence of complete address histories, low statistical power because of the low levels of radiation exposure and small numbers of childhood leukemia outcomes, limited understanding of the etiology of childhood leukemia (including relevant time windows of exposure and latency), and inability to adjust for potential confounders.<sup>83</sup>

#### **Long-term Effects: Tissue Reactions and Conditions Other Than Cancer**

##### *Tissue Effects After High-Dose Radiotherapy*

Compared with adults, children undergoing radiotherapy appear to experience higher risks of the harmful tissue reactions, other than cancer, that occur at relatively high radiation exposure levels. Valuable sources of data about adverse effects other than cancer associated with high-dose radiation exposures include follow-up studies of childhood cancer survivors.<sup>84–94</sup> These studies have

identified impairment of growth and maturation, neurologic effects (attributable to loss of brain volume or interference with myelination of nerve axons or development of synapses), cardiovascular system abnormalities, decreased pulmonary function, thyroid and other neuroendocrine effects (attributable to hypothyroidism, reduction in growth hormone secretion, other hormonal deficiencies, and primary gonadal failure in male individuals), reproductive effects, cataracts and cortical opacities, hearing and vestibular abnormalities, and a range of effects on teeth (the latter particularly notable among children younger than 5 years at exposure). Many of these studies lack detailed information on estimated organ doses.

##### *Tissue Effects After Low-to-Moderate Doses of Radiation Exposure*

Data are more limited on late effects, other than cancer, in relation to low-to-moderate doses of radiation exposure. Adverse effects on mental and cognitive function have been observed among children and adolescents undergoing scalp irradiation for tinea capitis<sup>95</sup> and among infants treated with radiation for hemangiomas on the face, head, or other sites.<sup>96</sup> Increased risks of lens opacities (eg, cortical and posterior subcapsular opacities) have been associated with low-to-moderate doses of radiation among infants irradiated for hemangiomas<sup>97</sup> and atomic bomb survivors exposed at young ages.<sup>98–101</sup> Internal exposure of children and adolescents to radioiodines from the Chernobyl nuclear accident has been associated with subsequent increased risks of nonmalignant thyroid nodules.<sup>102</sup> Similar increased risks of nonmalignant thyroid nodules have been observed among those exposed as children or adolescents to radioiodines from the fallout from the Semipalatinsk Test Site in Kazakhstan at the time of the



aboveground testing<sup>20</sup> as well as in those exposed at ages younger than 20 years to the atomic bombings in Hiroshima and Nagasaki.<sup>103</sup> Findings were inconsistent for radiation exposure and risk of hypothyroidism, hyperthyroidism, and measures of thyroid autoimmune disease from studies of Chernobyl residents exposed in childhood or adolescence.<sup>104–108</sup> High doses of ionizing radiation have long been associated with circulatory disease, but evidence for an association at lower exposure is more controversial. Authors of a meta-analysis of populations exposed in adulthood support a relationship between circulatory disease mortality and low and moderate doses of ionizing radiation.<sup>109</sup> Growing evidence has been used to link radiation exposure from the atomic bombings during childhood with subsequent risk of hypertension, stroke, and heart disease.<sup>110–112</sup> A few studies have evaluated health effects among those exposed in utero to radioiodines.<sup>113,114</sup>

## CONCLUSIONS

This technical report summarizes clinically relevant information about the characteristics, sources, and biological effects of radiation exposure to clarify the rationale for the specific measures to reduce radiation exposures and adverse health effects from a radiation emergency. Clinical and related

features of radiation-related health outcomes are described for short-term (eg, ARS), short- and long-term (eg, mental health conditions), and long-term (eg, cancer and tissue reactions and conditions other than cancer) effects. This report summarizes newer scientific data on cancer and other serious health effects from long-term follow-up of the Japanese atomic bomb survivors and the Chernobyl nuclear accident and populations exposed to aboveground nuclear testing. The health outcomes reported since the 2011 Fukushima Daiichi nuclear plant event are critically evaluated. Also described are short-term health effects from inappropriately discarded medical radiation equipment, of which there have been no long-term studies. In addition, results are scrutinized for the large number of studies of health effects among populations living in proximity to nuclear plants. Recommendations for pediatricians and the health care sector, government, and families can be found in the accompanying policy statement.<sup>9</sup>

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## ABBREVIATIONS

<sup>131</sup>I: iodine-131  
<sup>137</sup>Cs: cesium-137  
AAP: American Academy of Pediatrics  
ARS: acute radiation syndrome  
FDA: US Food and Drug Administration  
KI: potassium iodide  
SI: Système International d'Unités

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