Elevated Childhood Cancer Incidence Proximate to U.S. Nuclear Power Plants

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ABSTRACT. Numerous reports document elevated cancer rates among children living near nuclear facilities in various nations. Little research has examined U.S. rates near the nation's 103 operating reactors. This study determined that cancer incidence for children < 10 yr of age who live within 30 mi (48 km) of each of 14 nuclear plants in the eastern United States (49 counties with a population > 16.8 million) exceeds the national average. The excess 12.4% risk suggests that 1 in 9 cancers among children who reside near nuclear reactors is linked to radioactive emissions. If cancer incidence in 5 western states is used as a baseline, the ratio is closer to 1 in 5. Incidence is particularly elevated for leukemia. Childhood cancer mortality exceeds the national average in 7 of the 14 study areas.
<Key words: childhood cancer, ionizing radiation, leukemia, nuclear power plants, radioactive emissions>

IONIZING RADIATION poses a significant health risk to fetuses, infants, and children. Pelvic X-rays delivered to pregnant mothers raise cancer risk during childhood,[1,2] and increased background radiation is associated with elevated cancer levels among exposed children.[3–5] Ingestion of fission products is also linked with elevated childhood cancer levels. Temporal increases in leukemia and other cancers have been documented among children living near sites where large-scale atomic weapons tests were conducted in the 1950s and 1960s.[6–9] Thyroid cancer incidence rose sharply among children living in Belarus (especially the Gomel region) and the Ukraine after the 1986 accident at the Chernobyl plant.[10–12] Elevated thyroid cancer incidence in children in Belgium and northern England after the Chernobyl accident has also been reported.[13,14]

Childhood cancer is the most commonly used measure for evaluating health risks for persons living near nuclear installations. The young are more susceptible to radionuclides than adults because (a) a given dose is proportionally larger for a fetus or child than for an adult, (b) the fetus and young child are undergoing rapid cell growth and division during these life stages, and (c) the child undergoes increasing tissue differentiation in the maturation process.

Reports on childhood cancer near various nuclear plants in the United Kingdom have found higher than expected rates.[15–25] Most studies focus on leukemia, a condition that may be initiated by bone- and bone-marrow–seeking radioisotopes such as strontium-89 and -90, and barium-140. These fission products are not found in natural background radiation, but are exclusively byproducts of nuclear weapons explosions and nuclear reactor operations.

Elevated childhood cancer incidence rates proximate to nuclear facilities have been reported in Canada,[26] France,[27] Germany,[28] and the former Soviet Union.[29] Some of these reports conclude that a causal relationship exists between radiation exposure and childhood cancer risk, whereas others suggest only a statistical association. Still other reports on childhood cancer near nuclear installations have shown no risk from proximity to nuclear sites.

There are few studies of childhood cancer rates near nuclear facilities in the United States—the site of 103 of the world's 435 nuclear power reactors. The nation's 1st nuclear weapons reactor commenced operation in 1943; the 1st nuclear power reactor achieved initial criticality in 1957. The studies that have been conducted have been small in scope, with mixed results. Johnson[30] found an excess of cancer incidence (25 observed vs. 16 expected) in the period 1969 to 1971 among children 0–14 yr living < 13 mi (21 km) from the Rocky Flats weapons processing facility. Data from Hatch et al.[31] show that cancer cases in the area < 10 mi (16 km) from the Three Mile Island complex rose from 34 to 47 cases for children 0–24 yr in the 5 yr after the 1979 accident. Goldsmith reported excess leukemia mortality for children 0–9 yr in the 4 counties closest to the Oak Ridge and Hanford nuclear weapons installations in the 1950s and 1960s, but not in the 1970s.[32] Enstrom[33] found no excess cancer mortality near the San Onofre plant, but Johnson[34] documented that myeloid leukemia deaths among local children increased after the plant began operation.

Jablon et al.[35] reported a significant excess of leukemia incidence in children ages 0–9 yr who lived in 5 counties near 4 nuclear plants in Connecticut and Iowa, but no excess incidence for other childhood cancers, and no excess childhood leukemia/cancer deaths. The Jablon report compared cancer incidence near the Connecticut and Iowa plants with rates for each respective state, and compared cancer mortality with national rates. Cancer incidence and mortality for children < 10 yr in local counties exceeded state and national standards for each of the 4 areas. Moreover, the proportion of excesses for incidence and mortality was very similar (Table 1).

The Surveillance, Epidemiology and End Results (SEER) program of the U.S. Centers for Disease Control and Prevention collects data on 5 states and 4 metropolitan areas with established tumor registries, covering about 1/10 of the U.S. population. The SEER data show that, from 1998 to 2000, cancer incidence in children < 15 yr was 14.83 per 100,000, the highest since SEER was formed in 1973. From 1975 to 2000, cancer rates in children rose 31.7% for all types of cancers, and 39.6% and 49.6%, respectively, for leukemia and brain/other nervous system cancers, which make up over half of childhood malignancies.[36] The increasing trend in childhood cancer incidence has spurred considerable debate on its etiology; the U.S. Environmental Protection Agency has suggested that environmental pollutants are 1 potential cause.[37] Since the completion of the Jablon study, which included data only through 1984, many states have established cancer registries. Our study uses data from some of those registries to determine cancer incidence for children < 10 yr who live within 30 mi (48 km) of a nuclear plant in the eastern United States.

Materials and Method

Childhood cancer incidence and mortality were analyzed for 49 counties situated mostly or completely within 30 mi (48 km) of nuclear reactors in the eastern United States. The analysis focused on cancer in children < 10 yr who resided in the study counties at the time of diagnosis. The age category was selected to match that used by Stewart et al.[1]—who identified it as the period of elevated cancer risk after prenatal irradiation—and that used in the U.S. National Cancer Institute (NCI) study of cancer near nuclear facilities.[38]

The distance of < 30 mi (48 km) was selected because cancer rates at the subcounty level are generally not readily available, or are not reported because of

Table 1.—Incidence and Mortality, All Cancers, Persons Age 0–9 Yr, Counties near Nuclear Plants in Connecticut and Iowa, Compared to State (Incidence) and Nation (Mortality)

Plant, yr startup	Location	Yr included	Relative risk (*n*) Incidence	Relative risk (*n*) Mortality
Haddam Neck, 1967	Middlesex, CT	1968–1984	1.03 (45)	1.04 (18)
Millstone, 1970	New London, CT	1971–1984	1.12 (84)	1.13 (30)
Ft. Calhoun, 1973	Harrison, IA	1974–1984	1.55 (6)	1.94 (5)
Duane Arnold, 1984	Benton, IA, and Linn, IA	1975–1984	1.18 (50)	1.16 (16)
Total			1.12 (185)	1.15 (69)

Source: Jablon S, Hrubec Z, Boice JD, et al. Cancer in Populations Living near Nuclear Facilities. National Cancer Institute. NIH publ. no. 90-874. Washington, DC: U.S. Government Printing Office, 1990.

confidentiality rules imposed by various state tumor registries. The NCI examined cancer rates in counties closest to nuclear reactors; some of their locations are duplicated herein (e.g., Dade County, Florida; Westchester/Rockland Counties, New York; Plymouth County, Massachusetts).[38] Examining rates on a smaller scale might be of interest; however, achieving statistical significance would be difficult because only about 1/5 of the population in this study reside within 10 mi (16 km) of the operating reactors.

Establishing significant patterns for rare occurrences like cancers in children often requires multiple years of data. The years 1988 to 1997 were selected because a number of eastern states have comprehensive incidence registries for this period (Connecticut, Delaware, Florida, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island). Childhood cancer mortality data (ICD-9 rubric 140.0–239.9) is available for all states from 1988 to 1997.[39] The population-at-risk estimates we used to compute rates were obtained from the U.S. Centers for Disease Control and Prevention.[39]

Incidence and mortality data for total childhood cancers from 1988 to 1997 were examined for areas near 24 reactors and 14 nuclear plants still in operation at the end of 1997. The Seabrook reactor in New Hampshire was included, even though its initial criticality date was June 1, 1989. All other reactors were in operation for at least 4 yr prior to 1988.[40] The Three Mile Island and Peach Bottom plants are situated about 35 mi (56 km) apart. Because there is overlap of some counties, the 2 sites were combined to avoid double counting. All 24 reactors produce electric power, with the exception of Brookhaven, a government-operated complex of research reactors that also produces radioactive fission products. The nuclear plants and the 49 counties included in the analysis are given in Table 2.

Selected demographic characteristics of residents of the 49 counties were compared with those of the nation (Table 3). The 2000 U.S. Census reported > 16.8 million persons residing in these counties, an increase of 10.1% since 1990. In general, lower proportions of blacks, Hispanics, and poor persons lived in the study counties than in the nation as a whole, with some exceptions. In Miami-Dade County, Florida—the site of the Turkey Point reactors—20.3% and 57.3% of residents were black or Hispanic, respectively, compared with national percentages of 12.3% and 12.5%. In New York's Westchester and Rockland Counties, which flank the Indian Point nuclear installation, the black and Hispanic proportions slightly exceed those for the United States. Some overlap may exist between the 2 categories, as a small proportion of Hispanics are also reported as black.[41]

Leukemia, which accounts for about 1/3 of cancers diagnosed in children < 10 yr, was studied near the 5 nuclear plants in Pennsylvania, because this state's cancer registry makes age- and race-specific incidence data by type of cancer readily available. Pennsylvania makes up 39% of the population in the 14 regions we studied.

Local rates of childhood cancer and leukemia were compared with U.S. rates. The national standard for mortality represents all 50 states plus the District of Columbia. SEER data serve as a proxy for national incidence data. Incidence rates for 1988 to 1997 were calculated using the average rates for 1988 to 1992 and 1993 to 1997, for age groups 0–4 and 5–9 yr.[42,43] Incidence data for 1997 were unavailable for Connecticut, New York, and Rhode Island, so 1988 to 1996 rates

Table 2.—Nuclear Power Plants Included in the Study, with Dates of Reactor Criticality and Counties Located Mostly or Completely within 48 Km (30 Mi) of the Plant

Nuclear power plant	Date(s) of criticality	Counties mostly or completely within 48 km of the plant
Beaver Valley, Shippingport, PA	1976, 1987	PA: Allegheny, Beaver, Butler, Lawrence, Washington
Brookhaven, Upton, NY	1950	NY: Suffolk
Crystal River, Red Level, FL	1977	FL: Citrus, Hernando, Levy, Marion
Indian Point, Buchanan, NY	1973, 1976	NY: Rockland, Westchester
Limerick, Pottstown, PA	1984, 1989	PA: Berks, Chester, Delaware, Lehigh, Montgomery
Millstone, Waterford, CT	1975, 1986	CT: Middlesex, New London, Tolland, Windham RI: Kent, Washington
Oyster Creek, Forked River, NJ	1969	NJ: Monmouth, Ocean
Peach Bottom, Delta, PA, and Three Mile Island, Londonderry PA	1973, 1974, and 1974	PA: Cumberland, Dauphin, Lancaster, Lebanon, Perry, York
Pilgrim, Plymouth, MA	1972	MA: Plymouth
St. Lucie, Hutchinson Island, FL	1976, 1983	FL: Martin, St. Lucie
Salem/Hope Creek, Salem, NJ	1976, 1980, 1986	DE: Kent, New Castle NJ: Gloucester, Salem
Seabrook, Seabrook, NH	1989	MA: Essex NH: Rockingham, Strafford
Susquehanna, Berwick, PA	1982, 1984	PA: Carbon, Columbia, Luzerne, Montour, Schuylkill, Sullivan, Wyoming
Turkey Point, Florida City, FL	1972, 1973	FL: Miami-Dade

were used for the Brookhaven, Indian Point, and Millstone facilities. Data were unavailable for 3 counties < 30 mi (48 km) from 4 nuclear power reactors in the Rochester-Syracuse area in New York.

Of the SEER areas making up the national incidence standard, Hawaii, New Mexico, Utah, Atlanta, San Francisco, and Seattle have no nuclear facilities, and lie at least 100 mi (161 km) from any reactor operating since 1989. The 3 metropolitan Detroit counties are 20 to 40 mi (32 to 64 km) from the Fermi 2 reactor. A small proportion of Connecticut and Iowa residents live within 30 mi (48 km) of a reactor. Thus, the SEER rate suggests a relatively underexposed population to compare with those residing in the 49 counties studied.

Table 3.—Population in the U.S. and within 48 Km (30 Mi) of the Nuclear Power Plants in the Study, with Percentage of Blacks, Hispanics, and Population below the Poverty Line, 2000

Plant	Population	% black	% Hispanic	% below poverty line
United States	281,421,906	12.3	12.5	13.3
Beaver Valley	1,934,701	9.4	0.8	11.0
Brookhaven	1,419,369	6.9	10.5	7.6
Crystal River	542,253	7.7	4.9	15.6
Indian Point	1,210,212	13.4	14.3	9.4
Limerick	2,420,190	7.8	4.4	6.8
Millstone	950,250	3.0	3.6	7.0
Oyster Creek	1,126,217	5.8	5.7	7.1
Peach Bottom/Three Mile Island	1,481,810	5.2	3.9	7.4
Pilgrim	472,822	4.6	2.4	8.6
St. Lucie	319,426	11.4	7.9	13.1
Salem/Hope Creek	945,920	16.9	4.2	8.9
Seabrook	1,113,011	1.9	7.5	9.1
Susquehanna	645,411	1.5	1.1	10.6
Turkey Point	2,253,362	20.3	57.3	21.1
Total (49 counties)	16,834,954	9.2	12.4	10.4

Source: U.S. Census of Population, 2000.

Table 4.—Total Cancer Incidence per 100,000 with Number of Cases for Persons 0–9 Yr of Age Residing in Counties < 48 Km (30 Mi) from the Nuclear Plants in the Study, Compared with SEER* Rates, 1988–1997

	Age 0–4 yr		Age 5–9 yr		Total 0–9 yr		% difference from SEER rate			
Plant	Incidence	n	Incidence	n	Incidence	n	Age 0–4	Age 5–9	Total 0–9 yr	p
United States	20.20		10.80		15.50					
Beaver Valley	20.74	253	11.54	142	16.12	395	+2.7	+6.9	+4.0	
Brookhaven	23.30	207	12.30	100	18.04	307	+15.3	+13.9	+16.4	< 0.07
Crystal River	22.35	57	10.10	27	16.08	84	+10.6	−6.5	+3.8	
Indian Point	22.94	169	12.85	84	18.20	253	+13.6	+19.0	+17.4	< 0.08
Limerick	20.87	322	11.04	166	16.02	488	+3.3	+2.2	+3.3	
Millstone	20.71	117	10.93	61	15.85	178	+2.5	+1.2	+2.2	
Oyster Creek	24.82	179	14.29	101	19.61	280	+22.9	+32.3	+26.5	< 0.006
Peach Bottom/Three Mile Island	22.01	213	11.27	109	16.64	322	+9.0	+4.4	+7.4	
Pilgrim	22.95	77	12.64	43	17.76	120	+13.6	+17.1	+14.6	
St. Lucie	26.08	45	18.75	31	22.49	76	+29.1	+73.6	+45.1	< 0.03
Salem/Hope Creek	20.35	133	11.23	72	15.83	205	+0.7	+4.0	+2.2	
Seabrook	21.50	163	11.88	87	16.77	250	+6.4	+10.0	+8.2	
Susquehanna	21.25	80	13.95	56	17.48	136	+5.2	+29.1	+12.8	
Turkey Point	26.07	396	13.01	179	19.87	575	+29.1	+20.5	+28.2	< 0.001
Total (39 counties)	22.51	2,411	12.15	1,258	17.42	3,669	+11.4	+12.5	+12.4	
p							< 0.0002	< 0.002	< 0.00001	

*Surveillance, Epidemiology and End Results, Centers for Disease Control and Prevention, Atlanta, Georgia.
Sources: SEER and the state cancer registries of Delaware, Florida, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, and Rhode Island.

Table 5.—Number of Cases, Population, and Incidence per 100,000 for Total Cancers among Persons 0–9 Yr of Age Residing in Counties < 48 Km (30 Mi) from Nuclear Plants in the Eastern United States, Compared with the Remainder of the State, 1988–1997

Area	*n*	Population	Cases/100,000	% difference	*p*
Indian Point, Brookhaven	560	3,091,824	18.11	+12.1	< 0.055
Other New York	3,222	19,952,003	16.15		
Crystal River, St. Lucie, Turkey Point	735	3,754,294	19.58	+7.9	
Other Florida	2,607	14,362,311	18.15		
Oyster Creek, Salem	485	2,722,573	17.81	+5.7	
Other Delaware, New Jersey	1,553	9,217,923	16.85		
Millstone	178	1,123,275	15.85	+1.0	
Other Connecticut, Rhode Island	647	4,119,792	15.70		
5 Pennsylvania plants	1,341	8,209,264	16.34	+7.4	< 0.07
Other Pennsylvania	1,178	7,740,218	15.22		
Pilgrim, Seabrook	370	2,166,060	17.20	+4.8	
Other Massachusetts, New Hampshire	1,250	7,569,390	16.42		
Total 49 counties	3,669	21,067,290	17.43	+5.0	< 0.04
Other counties in 9 states	10,457	62,988,637	16.60		

Note: Data are for 1988 to 1996 for Connecticut, New York, and Rhode Island.
Sources: The state cancer registries of Delaware, Florida, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, and Rhode Island.

Results

Incidence of all cancers. Incidence for total cancers for children < 5 yr during 1988 to 1997 was higher than the SEER rate near all 14 nuclear plants in our study (Table 4). The rate for all 49 counties combined was 22.51 per 100,000, or 11.4% greater than the SEER rate ($p < 0.0002$). The smallest excess was near the Salem/Hope Creek complex (+0.7%); the largest occurred near both the Turkey Point and St. Lucie facilities in Florida (+29.1%).

Cancer incidence in children 5–9 yr for 1988 to 1997 exceeded the SEER rate for 13 of the 14 areas. The rate for the study counties was 12.15 per 100,000—12.5% higher than the SEER rate of 10.80 ($p < 0.002$). The smallest excess was found near the Millstone reactors in Connecticut (+2.2%), and the largest occurred near St. Lucie (+73.6%). Incidence near the Crystal River facility in Florida was 6.5% below the SEER rate.

Combining the age groups yields an incidence rate of 17.42 per 100,000—12.4% above the SEER rate ($p < 0.00001$). The excess incidence near 3 of the plants (Oyster Creek, St. Lucie, and Turkey Point) was statistically significant; near the Indian Point and Brookhaven facilities it reached borderline significance ($p < 0.08$ and $p < 0.07$, respectively). Although county-specific totals are not shown, considerable variation in rates exists, in part because of the relatively small numbers of cases involved. Still, the incidence rate for those 0–9 yr of age exceeded the U.S. rate in 38 of the 49 study counties.

Table 6.—Cancer Incidence (per 100,000) for Persons 0–9 Yr of Age, by Race for Counties < 48 Km (30 Mi) from Nuclear Plants vs. Other Counties in Pennsylvania, 1988–1997

Race	*n*	Population	Cases per 100,000 Local	Cases per 100,000 Pennsylvania	% difference
White	1,189	7,319,688	16.24	15.88	+2.3%
Black	105	742,561	14.14	13.28	+6.5%

Source: Pennsylvania State Cancer Registry.

Childhood cancer incidence < 30 mi (48 km) from nuclear reactors was compared with rates for the remaining counties in the states in which reactors are located. Several adjoining, less-populated states (New Jersey and Delaware, Connecticut and Rhode Island, Massachusetts and New Hampshire) were combined to ensure adequate statistical power. For each of 6 states and combinations of states, cancer incidence for those 0–9 yr in the counties near reactors was higher than in other counties in the state (Table 5). The total excess incidence derived from comparing the counties near reactors with those in the rest of the state, or state combinations, was 5.0% ($p < 0.04$). Elevated rates for the New York and Pennsylvania nuclear counties are of borderline significance ($p < 0.055$ and $p < 0.07$, respectively).

Total cancer incidence by race. U.S. black and Hispanic children < 20 yr of age have cancer incidence rates 23% and 10% below that for whites, respectively.[44] To assess the effect of race on childhood cancer incidence near nuclear plants, incidence data from Pennsylvania counties near nuclear plants were studied (the Pennsylvania registry makes county statistics for whites and blacks more readily available than do registries in other states). Using SEER data, the 1988 to 1997 U.S. cancer incidence rates for white and black children 0–9 yr were calculated at 15.88 and 13.28 per 100,000, respectively. For the 23 Pennsylvania counties located close to reactors, childhood cancer rates exceeded U.S. rates for both whites and blacks (Table 6).

Table 7.—Incidence of Leukemia and All Other Cancers for Persons 0–9 Yr of Age for Counties < 48 Km (30 Mi) from Nuclear Plants, and Other Counties in Pennsylvania, Compared with SEER* Rates, 1988–1997

Area	*n*	Population	Cases/100,000	% difference from SEER rate	*p*
		Leukemia			
United States			5.30		
Pennsylvania			5.30		
Beaver Valley	144	2,449,693	5.88	+10.9	< 0.06
Limerick	171	3,046,972	5.61	+5.9	
Peach Bottom/Three Mile Island	112	1,934,559	5.79	+9.2	
Susquehanna	55	778,040	7.07	+33.4	< 0.04
Total	482	8,209,264	5.87	+10.8	< 0.01
Other Pennsylvania	363	7,740,218	4.69	–11.5	
		All other cancers			
United States			10.20		
Pennsylvania			10.50		
Beaver Valley	251	2,449,693	10.25	+0.5	
Limerick	317	3,046,972	10.40	+2.0	
Peach Bottom/Three Mile Island	210	1,934,559	10.86	+6.4	
Susquehanna	81	778,040	10.41	+2.1	
Total	859	8,209,264	10.46	+2.6	
Other Pennsylvania	815	7,740,218	10.53	+3.2	

*Surveillance, Epidemiology and End Results, Centers for Disease Control and Prevention, Atlanta, Georgia.
Sources: SEER data and the Pennsylvania State Cancer Registry.

Table 8.—Cancer Mortality near Nuclear Plants for Persons 0–9 Yr of Age, Compared with U.S. Rates, 1988–1997

Plant	Deaths	Population	Deaths/100,000	% difference from U.S. rate
United States	13,241	378,858,024	3.49	
SEER areas	1,255	35,942,869	3.49	
Beaver Valley	78	2,449,693	3.18	–8.9
Brookhaven	56	1,896,531	2.95	–15.5
Crystal River	11	522,266	2.11	–39.7
Indian Point	55	1,551,301	3.55	+1.4
Limerick	102	3,046,972	3.35	–4.2
Millstone	32	1,249,007	2.56	–26.7
Oyster Creek	65	1,427,943	4.55	+30.2
Peach Bottom/Three Mile Island	89	1,934,559	4.60	+31.6
Pilgrim	24	675,674	3.55	+1.6
St. Lucie	15	337,853	4.44	+27.0
Salem/Hope Creek	45	1,294,630	3.48	–0.5
Seabrook	65	1,490,386	4.36	+24.8
Susquehanna	28	778,040	3.60	+3.0
Turkey Point	89	2,894,175	3.08	–12.0
Total	754	21,549,030	3.50	+0.1

Source: National Center for Health Statistics, Mortality Data File.

Incidence of leukemia. We examined the incidence of childhood leukemia in the 23 counties near 5 nuclear plants in Pennsylvania (Table 7). These regions account for slightly more than half the state's population. Leukemia incidence in the state's nuclear counties exceeded the U.S. rate by 10.8%; the rate for the remainder of the state was 11.5% below the U.S. rate ($p < 0.01$). For all other cancers, virtually no difference was seen between nuclear and non-nuclear counties, even though both exceeded the national rate (by 2.6% and 3.2%, respectively).

Mortality. Cancer mortality for U.S. children < 10 yr of age for 1988 to 1997 was 3.49 per 100,000; it was the same for the SEER areas. Cancer mortality for children < 10 yr was higher than the U.S. rate in 7 of the 14 study areas (Table 8). Because cancer mortality represents only 20% of cancer incidence in children, area-specific numbers of deaths are relatively small, and none of the differences achieved statistical significance. A total of 218 leukemia deaths occurred among children < 10 yr in the 49 counties during the 10-yr study period, resulting in a mortality rate of 1.012 per 100,000 (1.6% below the U.S. rate).

Discussion

Few studies of childhood cancer among American children living near nuclear reactors exist. Unlike exposure to external radiation sources such as cosmic rays or X-rays, radioactive nuclides are deposited within the body from food and water. The fetus receives these exposures through the mother's diet during pregnancy. Once in the body, these unstable atoms release alpha, beta, and gamma radiation that damages dividing cells. When a damaged cell is unable to repair itself, an aberrant cell line, or malignancy, may result.

This study found a consistent pattern of increased childhood cancer incidence in all study areas < 30 mi (48 km) from nuclear plants in the eastern United States. Our findings support the biologically plausible concept that susceptibility to carcinogens, such as radioactivity, is greatest in utero and in early childhood. They also support numerous analyses documenting elevated childhood cancer rates near nuclear facilities in the United States and other nations. The finding that cancer incidence for children < 10 yr is 12.4% greater in the study counties than the U.S. as a whole suggests that emissions from nuclear power plants may be linked with 1 of 9 local cases of childhood cancer. These descriptive epidemiological findings suggest a relationship between radioactive nuclides and childhood cancer and should be taken seriously in future research.

In Pennsylvania, childhood leukemia incidence in counties near nuclear plants exceeded U.S. rates by 10.8%; however, rates were 11.5% below the U.S. rate for all other areas of the state. This finding supports the considerable evidence that, although the risk of all forms of childhood cancer is increased by radiation exposure, the risk may be greatest for leukemia.

Childhood cancer incidence in nuclear counties showed significant excess when compared with other parts of the state, although this excess is not as great when the U.S. is used as a comparison group. Although reasons for this are not completely understood, it cannot be assumed that living more than 30 mi (48 km) from a nuclear reactor precludes residents from risk. Airborne emissions are carried by prevailing winds for long distances. Moreover, radioactive particles that are introduced into the diet through precipitation into drinking water, milk, and food may be transported considerable distances before consumption.

Cancer incidence rates for children living near nuclear reactors in Pennsylvania exceed national rates for both whites and blacks. No attempt was made to assess the effect of poverty on cancer rates. However, any elevated cancer rate from lack of access to medical screening does not occur among children, who are not routinely screened for cancer as older persons are. On the basis of SEER data, the 1988 to 1997 U.S. cancer incidence rate for blacks age 0–9 yr was 13.28 per 100,000, or 16% below the 15.88 per 100,000 rate for whites. The fact that Miami-Dade County Florida—with a population that is 77% black and Hispanic—has the 2nd highest childhood cancer incidence rate of the 14 areas studied suggests that racial composition is not the primary factor affecting the elevated rates documented herein.

Incidence rates are taken from multiple state-operated cancer registries, each with its own methods of data collection. Thus, the reliability of interstate comparisons may be compromised. However, because all children with cancer are treated in hospitals (the primary source of cancer incidence data in all states), reporting is likely to approximate completeness. If older, more established registries have more complete reporting, it was not apparent. The Connecticut Tumor Registry was established in 1935, well before any other registry, yet the Connecticut childhood cancer rate is 1 of the lowest in this report.

A precise evaluation of cancer risk for children living near nuclear reactors requires a comparison with an "unexposed control" group, but such a group is difficult to identify. Rates in counties situated > 30 mi (48 km) from reactors in the same state may not prove adequate, because radioactive particles travel considerable distances. The SEER rate for 9 U.S. cities and states may also be an inflated "control" group because these locations contain several nuclear reactors.

Five contiguous states in the western United States that have never had an operating nuclear power reactor and whose borders lie > 100 mi (161 km) from any reactor have a 1988 to 1997 cancer incidence rate for children 0–9 yr (n = 1,550) of 14.27 per 100,000. This figure is 22.1% lower than the rate for the 49 counties near reactors. Residents of these 5 states (Idaho, Nevada, New Mexico, Utah, and Wyoming) may or may not be representative of the U.S., using various criteria. However, they do represent perhaps the segment of the American population least exposed to radioactive emissions from reactors since the late 1980s. Using these 5 states as a control, the excess incidence near nuclear plants is close to 1 in nearly 5 childhood cancer cases (17.42 vs. 14.27 per 100,000). Even this may be a conservative estimate because the food supply in these western states contains some reactor-generated radioactivity from distant imports. Moreover, 3 nuclear weapons laboratories (Idaho National, Sandia, and Los Alamos) that discharged radioactivity in the western areas operated until about 1990.

No difference was seen in mortality rates between nuclear counties and the United States as a whole for cancer and leukemia among children < 10 yr. This finding differs from earlier data for Connecticut and Iowa counties, which showed parallel excesses for both incidence and mortality.[38] It is possible that the considerable enhancements in therapeutic interventions for childhood cancer have altered this prior pattern. From 1973 to 1998, annual mortality from cancer in U.S. children 0–14 yr declined by more than half (from 5.5 to 2.5 per 100,000). Survival from leukemia, especially acute lymphocytic leukemia, has improved most rapidly.[36,42] New treatments are so effective that high-incidence areas may often have below-average death rates.

Limitations. Our study had several limitations. First, the precise national cancer incidence rate is unknown in the United States, which lacks a centralized tumor registry system. We used SEER data—a sample representing < 10% of the U.S. population—to approximate the national incidence rate. Numerous government agencies confidently use these data as the national standard. Moreover, the 1988 to 1997 cancer mortality rate for children < 10 yr of age in the SEER areas equals that for the U.S. as a whole, suggesting that the SEER data are a relatively accurate proxy for the entire nation.

Second, this study examined cancer patterns in only 14 plants, which include 24 (plus the Brookhaven research reactors) of the 103 operating power reactors in U.S. plants. Seven of 16 eastern states did not have 10 yr of cancer incidence data available. These 7 states contain an additional 23 reactors at 13 plants, nearly equal to the 24 reactors at 14 plants analyzed here.[40]

Of the 24 reactors in the study, 13 (54%) achieved initial criticality before 1977. The proportion is 42% (33 of 79) for all other U.S. reactors, making the study reactors slightly older than average.[40] The study reactors are also located in the more industrialized eastern part of the country, which may affect cancer rates. About 1/3 of the 50 million Americans living within 30 mi (48 km) of a nuclear power reactor live near these 14 plants.

A 3rd limitation existed because few of the 50 states compiled cancer incidence statistics prior to the late 1980s, thus it is not possible to analyze data over the entire operating life of the reactors. Information on the birth location of children with cancer living near nuclear plants is not easily available. The effects of in-migration should be addressed in future studies.

Our study leaves a number of points unaddressed. Understanding patterns by type of childhood cancer would enhance knowledge of any radiation–cancer link. Analyzing data for adolescents and young adults would also improve this understanding. Cancer patterns for residents living beyond the 30-mi (48-km) radius from reactors would provide helpful information, as would comparisons of downwind and upwind populations near plants. Comparing interregional childhood cancer patterns by precipitation level might provide useful information, as well. Including areas near other U.S. reactors would make this study part of a more comprehensive analysis.

Perhaps most importantly, the findings from our study should be compared with doses of ionizing radiation. Emissions from nuclear plants can be employed, as well as levels of various radionuclides in the air, water, food, and soil. Comparing childhood cancer risk to in vivo levels of radioactivity offers the most valuable evidence for this type of study. An effort is currently being made to measure radioactive strontium-90 in baby teeth at birth; a link between trends in concentrations of this isotope and childhood cancer incidence in Suffolk County, New York, has recently been reported.[45] Knowing in vivo levels of manmade ionizing radiation will eventually enable case-control and prospective studies to proceed. The strong evidence of high childhood cancer levels near nuclear plants presented in this report indicates that such follow-up studies will be critical.

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