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Childhood cancer mortality in relation to the St Lucie nuclear power station

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Abstract
An unusual county-wide excess of childhood cancers of brain and other nervous tissue in the late 1990s in St Lucie County, Florida, prompted the Florida Department of Health to conduct a case–control study within the county assessing residential chemical exposures. No clear associations were found, but claims were then made that the release of radioactive substances such as strontium 90 from the St Lucie nuclear power station, which began operating in 1976, might have played a role. To test the plausibility of this hypothesis, we extended by 17 years a previous study of county mortality conducted by the National Cancer Institute. Rates of total cancer, leukaemia and cancer of brain and other nervous tissue in children and across all ages in St Lucie County were evaluated with respect to the years before and after the nuclear power station began operation and contrasted with rates in two similar counties in Florida (Polk and Volusia). Over the prolonged period 1950–2000, no unusual patterns of childhood cancer mortality were found for St Lucie County as a whole. In particular, no unusual patterns of childhood cancer mortality were seen in relation to the start-up of the St Lucie nuclear power station in 1976. Further, there were no significant differences in mortality between the study and comparison counties for any cancer in the time period after the power station was in operation. Relative rates for all childhood cancers and for childhood leukaemia were higher before the nuclear facility began operating than after, while rates of brain and other nervous tissue cancer were slightly lower in St Lucie County than in the two comparison counties for both time periods. Although definitive conclusions cannot be drawn from descriptive studies, these

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data provide no support for the hypothesis that the operation of the St Lucie nuclear power station has adversely affected the cancer mortality experience of county residents.

1. Introduction

From time to time, reports of clusters of cancer cases raise concern over possible excessive exposure to environmental or industrial toxins. An apparent county-wide increase in childhood cancers of brain and other nervous tissue in St Lucie County, Florida (15 cases over the 3 year period 1995–97; expected incidence 3.7 cases) prompted the Florida Department of Health (FDOH) and the Agency for Toxic Substances and Disease Registry to conduct a case–control investigation to learn whether a wide range of chemicals might be associated with the occurrence of such cancers (FDOH 2001, ATSDR 1998). Cases selected for study were children under the age of 20 diagnosed with brain and other nervous tissue cancers over the years 1981–97 in St Lucie County (29 cases in all). Fifteen controls were selected and measurements for chemical exposure were made in the homes of cases and controls. None of the over 500 chemicals evaluated was linked to the occurrence of childhood cancer. Subsequently, it was purported that the St Lucie nuclear power station, which began operation in 1976, might be causally related to the occurrence of these childhood malignancies, conceivably from the radioactive strontium and other radionuclides released during operation (Mark 2003, Mangano *et al* 2003). To test the plausibility of this hypothesis, we extended by 17 years a previous study of mortality in counties with nuclear facilities conducted by the National Cancer Institute (NCI) (Jablon *et al* 1990, 1991). We calculated rates of childhood and adult cancer, leukaemia and cancer of the brain and other nervous tissue in St Lucie County with respect to the years before and after the nuclear power station began operation and compared them with rates in similar counties in Florida.

2. Methods

The same methodology, computer programs and databases as used in the earlier NCI investigation (Jablon *et al* 1990) were extended for use in this St Lucie County mortality survey. Similar methodologic approaches also have been used to evaluate cancer risk in communities living in areas of increased radiation from mining, milling and uranium processing operations (Boice *et al* 2003a, 2003b).

2.1. Cancers considered for study

Because of the reports of possible elevations of childhood cancers in St Lucie County, cancers occurring under the age of 20 were selected for study with special emphasis on leukaemia and cancer of the brain and other nervous tissue. Neuroblastoma, a cancer arising from sympathetic nervous tissue, is also included within the combined brain and other parts of the nervous system category (ICD8 191, 192). For completeness, we also assessed rates of these cancers across all ages.

2.2. Mortality data

Cancer mortality data for all counties in the state of Florida were available from the NCI for the years 1950–2000 (NCI 2003). Counties are the smallest areas for which both population

Table 1. Demographic and socioeconomic characteristics of St Lucie and the two comparison counties (Polk, Volusia) in Florida from 1990 census data (USDC 1992).

			Per cent[a]								
County	Total persons	Popn density	Male	White	Rural	HS grad+	Age <18	Age 65+	Employed	Below poverty	Med HH income ($)
Study county											
St Lucie	150 171	262.3	48.8	81.8	7.9	71.0	23.2	21.2	51.7	12.8	27 710
Selected comparison counties											
Polk	405 382	216.2	48.4	84.4	29.7	67.6	24.1	18.6	54.0	12.6	25 216
Volusia	370 712	335.2	48.4	88.7	16.1	75.5	19.7	22.8	51.0	11.8	24 818
Both comparison counties	776 094	260.4	48.4	86.5	23.2	71.5	22.0		20.6	12.2	25 028
State of Florida	12 937 926	239.6	48.3	83.1	15.2	74.3	22.1	18.3	57.0	12.4	27 483

[a] HS grad denotes high school graduate; Med HH income denotes median household income; Popn density denotes population density in persons per square mile.

estimates and annual counts of the number of deaths for specific causes are readily available back to 1950 from the National Center for Health Statistics and the US Census Bureau (NCI 2003).

2.3. Selection of study and comparison counties

The study county, St Lucie County, is located on the east coast of Florida, south of Cape Canaveral. Over 180 000 people live in St Lucie County today, but the population has increased over the years from in migration. In 1950, the population was only 21 000. Port St Lucie is the largest city with a population of about 80 000 residents. To select counties for comparison, 1990 Census Bureau demographic data on ten socioeconomic variables were obtained for St Lucie County and for all other counties in Florida (USDC 1992). The variables included population density (total persons divided by county area), percentage male, percentage white, percentage rural, percentage high school graduate, percentage under the age of 18 years, percentage over the age of 64 years, percentage employed, percentage below poverty and median household income. For each demographic characteristic, all 67 counties within the state of Florida were ranked 1–67 according to how similar the demographic value was to that of St Lucie County. The scores for each demographic characteristic were then summed for each county. Polk and Volusia Counties had the lowest scores, i.e., had characteristics closest to those of St Lucie County, and were selected as comparison counties (table 1, figure 1). The determination of a socioeconomic score based on area-level characteristics is similar to that done in other studies (Steenland *et al* 2004). Data on diet, smoking and other potential cancer risk factors are not readily available at the county level, but choosing comparison counties from the same region as the study county helps minimise differences in these and other factors.

In 1990, the total numbers of residents within St Lucie and the two comparison counties were 150 171 and 776 094, respectively (table 1). The comparison counties were similar to the study counties with regard to demographic indicators of cancer risk such as age, race and various measures of socioeconomic status. The majority of the population studied was white (over 82%); 22–23% of the county residents were under age 18 years; 21% were older than 64 years; over 71% had graduated from high school; and 52% were employed. The median household income in 1990, about $25 000 to $28 000 per year, was also similar between the study and comparison county populations. Comparison counties were more rural (23% versus

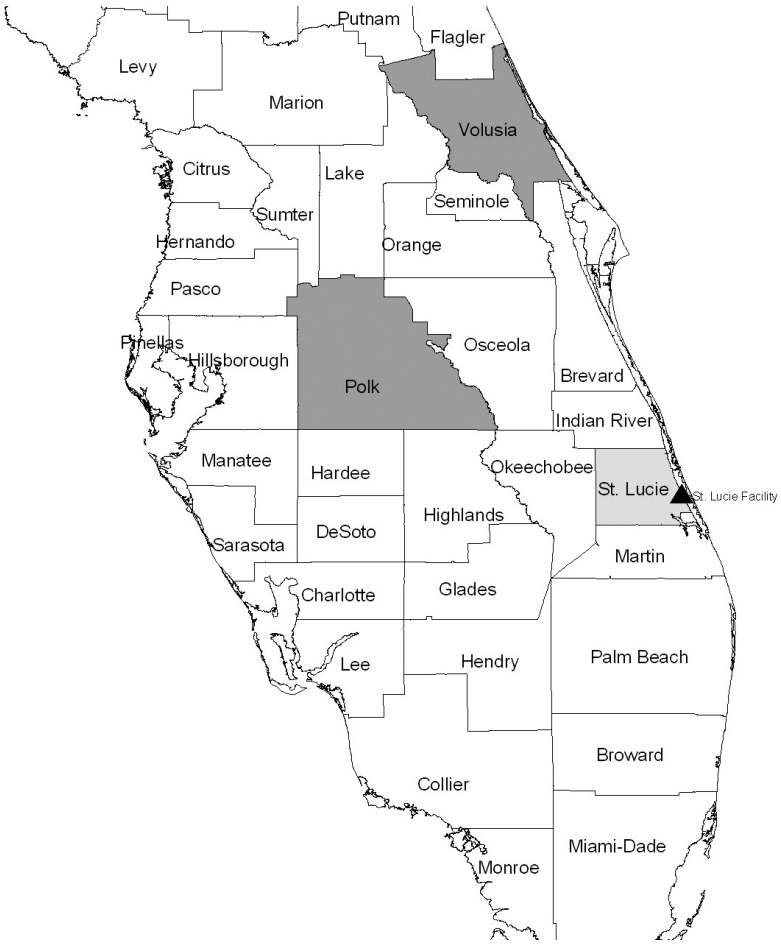

Figure 1. County map of Florida state indicating the study county (St Lucie) with the nuclear power station that began operating in 1976 and the two comparison counties (Polk, Volusia).

7%) than the study county, but were similar with regard to percentage below the poverty level (12% versus 15%).

2.4. Statistical analyses

Counts of deaths by cause, sex, race, and five-year age group were obtained for the three selected counties for each year from 1950 to 2000. Estimated annual county populations by sex, race, and five-year age group for the years 1950–69 were obtained by interpolation in decennial census counts as described by Riggan *et al* (1983). For the period after 1970, annual population estimates were prepared by the Bureau of the Census utilising not only the decennial censuses, but mid-decade sampling and other data such as school enrolment, public assistance programmes and immigration records (Jablon *et al* 1990, NCI 2003). For each type of cancer and each county the 'expected' number of deaths, based on concurrent US experience, was calculated for the 51-year study period (Marsh *et al* 1998, NCI 2003). The expected numbers

were obtained by multiplying annual US cancer death rates by the estimated populations, stratified by five-year age group and sex. Counts of observed and expected deaths were then summed over the following time periods: 1950–75 (just before the operation of the St Lucie nuclear power station), 1976–2000 (for the years after the nuclear reactor began operation) and 1950–2000 (all years before and after reactor operation). The minimum latency period for the development of solid cancer following radiation exposure is about 5–10 years and for leukaemia about 2 years (UNSCEAR 2000). Prenatal exposures have been associated with increased mortality under the age of 2 years for leukaemia and solid cancers in some studies (Bithell and Stewart 1975) and no excesses are reported after about 10–12 years in other studies (Monson and MacMahon 1984). Thus, there was ample opportunity for residents in St Lucie County to accumulate any dose and for trends in cancer rates to be evaluated. This approach is the same as done previously by the NCI using similar databases and statistical programs (Jablon *et al* 1990, 1991). Analyses excluding the first 10 years after reactor start-up in 1976 were also conducted.

The ratio of the actual number of deaths observed to the number expected is the standardised mortality ratio (SMR). Ratios of the standardised mortality ratios for the study to the control counties were called 'relative rates' (RRs). Ninety-five per cent confidence intervals were calculated for each RR following the method described in the NCI study (Mantel and Ederer 1985, Breslow and Day 1987, Jablon *et al* 1990). A 95% confidence interval that contains 1.00 indicates that the difference in mortality between St Lucie and the comparison counties was not statistically significant.

Age-standardised total cancer mortality rates are also computed for children under the age of 20 residing in St Lucie County contrasted with the age-standardised rates for children residing in the two comparison counties from 1950 to 2000. The rates are presented as five-year moving averages to smooth out fluctuations that occur when studying relatively small populations where the number of cases, i.e., childhood cancers, varies from year to year.

Because of the rarity of childhood cancer, broad categories of cancer type and calendar year had to be used to comply with confidentiality requirements for using the NCI and National Center for Health Statistics database, i.e., strata containing three or fewer cancer deaths could not be presented. The concern is the possibility that individuals with certain characteristics might be identified if the number of deaths were small.

3. Results

Table 2 presents, for both sexes combined, the number of deaths from leukaemia, cancers of the brain and other nervous tissue, and all cancers in childhood and across all ages during the years 1950–2000 in St Lucie County and the two comparison counties. Childhood cancer deaths were relatively rare during the 51-year period, with only 57 deaths in total occurring in St Lucie County and 354 in Polk and Volusia Counties.

Table 3 presents, for both sexes combined, the standardised mortality ratios (SMR) and relative rates (RR) of mortality for selected cancers in St Lucie County compared to the two comparison counties for the time periods before 1976, when the nuclear power station began operating, and after 1976. None of the SMRs for St Lucie County after the power station was in operation was significantly elevated. Furthermore, across all ages, total cancer rates in St Lucie County were the same as those in the control counties (RR 1.00; 95% CI 0.98–1.02). Similarly, for all childhood cancers there were no significant differences overall between the rates in St Lucie and the comparison counties (RR 1.07; 95% CI 0.79–1.42). The rate of childhood leukaemia was nonsignificantly higher in St Lucie County (RR 1.36; 95% CI 0.87–2.10) than the comparison counties, but this was due to an elevated rate prior to the start of

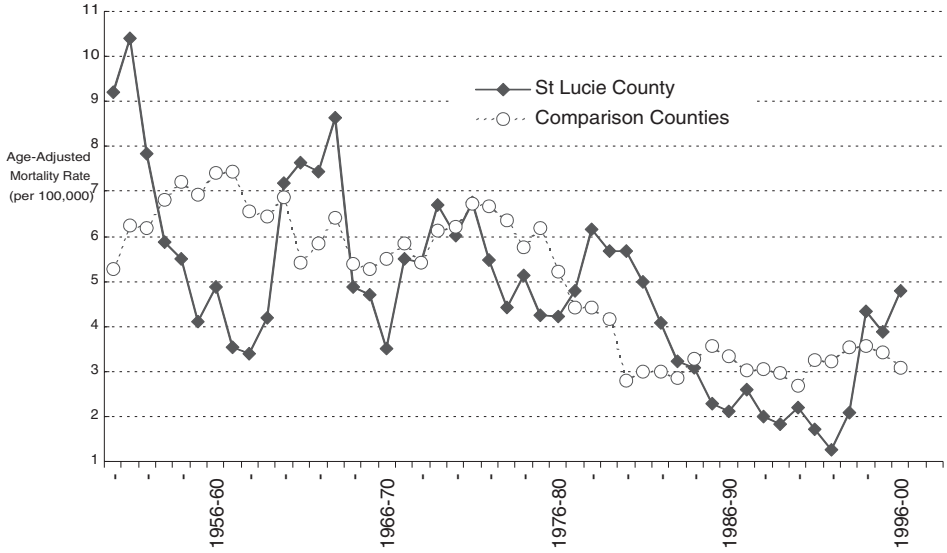

Figure 2. Age-standardised cancer mortality rates for children under the age of 20 residing in St Lucie County from 1950 to 2000 compared with age-standardised rates in the two comparison counties (Polk and Volusia). Five-year moving averages are presented to smooth fluctuation due to the relatively small number of childhood cancers occurring over these years.

Table 2. Number of cancer deaths occurring in St Lucie County and in the two comparison counties (Polk, Volusia) in Florida, 1950–2000.

	Number of deaths	
Cancer (ICD-8)	St Lucie County	Comparison counties
Childhood leukaemia (204–208)[a]	24	122
Childhood brain and other nervous tissue (191, 192)[a]	13	89
All childhood cancers (140–208)[a]	57	354
All leukaemia (204–208)	378	2 529
All brain and other nervous tissue (191–192)	261	1 425
All cancers (140–208)	11 411	66 602

[a] For ages under 20 years.

the nuclear facility (RR 1.91), whereas the rate was lower thereafter (RR 0.84). The rate of childhood brain and other nervous tissue cancers was slightly lower in St Lucie County overall (RR 0.94; 95% CI 0.52–1.68) and for both time periods (RR 0.87 and 0.96). Of the 18 RRs presented in table 3, eight were less than 1.00, four were essentially 1.00, and six were greater than 1.00; a distribution consistent with the play of chance when making multiple comparisons.

Analyses were also conducted excluding the first 10 years after the reactor start-up, i.e., for years 1985–2000. Essentially the same patterns were seen, although the relative rates were somewhat lower: 0.93 (95% CI 0.4–2.4), 0.78 (95% CI 0.3–2.0) and 0.96 (95% CI 0.6–1.6) for childhood leukaemia, childhood brain and other nervous tissue and all childhood cancers, respectively.

Figure 2 presents the age-standardised total cancer mortality rates for children residing in St Lucie County contrasted with the age-standardised rates for children residing in the two

Table 3. Relative rates (RRs) of mortality due to childhood (<20 yr) and other cancers in St Lucie County, Florida contrasted with the two comparison counties (Polk, Volusia) in Florida for two time periods during 1950–2000 for both sexes combined. The St Lucie nuclear power station began operation in 1976.

Cancer	Obs[a]	SMR[b]	(95% CI)	RR[c]	(95% CI)	Obs[a]	SMR[b]	(95% CI)	RR[c]	(95% CI)	Obs[a]	SMR[b]	(95% CI)	RR[c]	(95% CI)
Childhood leukaemia	16	1.48	(0.85, 2.41)	1.91	(1.11, 3.24)	8	0.74	(0.32, 1.47)	0.84	(0.40, 1.76)	24	1.12	(0.71, 1.66)	1.36	(0.87, 2.10)
Childhood brain and other nervous tissue	5	0.89	(0.29, 2.08)	0.87	(0.35, 2.20)	8	1.13	(0.49, 2.23)	0.96	(0.39, 2.06)	13	1.03	(0.55, 1.75)	0.94	(0.52, 1.68)
All childhood cancers	26	0.97	(0.63, 1.42)	1.11	(0.74, 1.67)	31	0.99	(0.67, 1.41)	1.02	(0.69, 1.49)	57	0.98	(0.74, 1.27)	1.07	(0.79, 1.42)
All leukaemia	73	0.85	(0.67, 1.07)	0.92	(0.72, 1.17)	305	0.83	(0.74, 0.93)	0.90	(0.80, 1.02)	378	0.84	(0.75, 0.92)	0.90	(0.81, 1.01)
All brain and nervous tissue	37	0.88	(0.62, 1.21)	0.88	(0.62, 1.12)	224	1.07	(0.93, 1.22)	1.10	(0.95, 1.27)	261	1.04	(0.91, 1.17)	1.06	(0.93, 1.20)
All cancers	1918	0.93	(0.88, 0.97)	1.02	(0.98, 1.07)	9,493	0.94	(0.92, 0.96)	0.99	(0.97, 1.01)	11 411	0.94	(0.92, 0.96)	1.00	(0.98, 1.02)

[a] Observed number of cancer deaths in St Lucie county.
[b] SMR (standardised mortality ratio) denotes the observed number of deaths in St Lucie county divided by the expected number of deaths based on rates in the general population of the United States.
[c] RR denotes the relative rate taken as the SMR in St Lucie county divided by the SMR in the two comparison counties.

comparison counties from 1950 to 2000. There is no consistent divergence in the patterns of childhood cancer between the study and comparison counties for the 51-year period.

4. Discussion

There was no evidence that the rates of childhood leukaemia, childhood brain and other nervous tissue cancer or all childhood cancers taken together were different in St Lucie County from the rates observed in the two similar counties or compared to expectations based on national cancer mortality rates over the 26-year period 1976–2000. Indeed, relative rates for all childhood cancers and for childhood leukaemia were slightly higher before the nuclear power station began operating in 1976 than afterwards, and rates of brain and other nervous tissue cancer were slightly lower in St Lucie County than in the two comparison counties for both time periods. These data provide no support for the hypothesis that radiation releases from the nuclear reactor may have increased the rates of childhood cancer.

4.1. Radiation exposure

Radiation from the normal operation of nuclear facilities is regulated, and only small levels are allowed to be released (CFR 2005). Thus the population dose from any radioactive releases would be expected to be much lower than from other sources of radiation, including from natural background (Darby and Doll 1987) or medical x-ray. Federal studies of populations living in counties containing nuclear facilities in the United States have found no evidence for increases in childhood cancer, leukaemia, breast cancer or any other cancer (Jablon *et al* 1990, 1991).

The previous study conducted by NCI included an evaluation of cancer mortality in St Lucie County prior to 1976 when the nuclear power station first operated, with follow-up until 1984 (Jablon *et al* 1990). We were able to extend the period of observation for an additional 17 years to 2000. Although the number of cancer deaths in children increased by a factor of three with the extended follow-up, the SMRs were essentially the same, 0.99 ($n = 31$) in our study and 1.13 ($n = 10$) in the NCI study. There have been many other studies in the past two decades concerning the occurrence of cancer around nuclear installations (IARC 2000). No consistent patterns have emerged to link radioactive release to increased cancer risk.

Recently, there have been claims that radioactive strontium had been found in deciduous teeth of children living near nuclear power plants and that this exposure may be responsible for increases in childhood cancer, breast cancers and other malignancies (Gould *et al* 2000, Mangano *et al* 2003). The US Nuclear Regulatory Commission reviewed these claims in response to a request from the New Jersey Department of Environmental Protection and concluded that they were unfounded (NRC 2001). The major source of radioactive strontium in the environment comes not from the operation of nuclear power plants, which is miniscule, but from prior aboveground testing of nuclear weapons (UNSCEAR 2000). Nuclear power plant emissions of radioactive strontium are 'inconsequential compared with other man-made sources and should be undetectable in deciduous teeth' (NRC 2001). Finally, strontium is similar to calcium in its chemical properties and would be taken up primarily by bone and not brain or nervous system tissues (ICRP 2000, IARC 2001). Thus, excessive exposure to radioactive strontium would not be expected to increase the occurrence of brain cancer or other nervous tissue cancer because the tissues responsible for these malignancies would receive little to no exposure.

4.2. Cluster of nervous tissue cancers

The cluster that initially drew attention to St Lucie County involved a total of 15 cases of childhood cancer of brain and other nervous tissue diagnosed over the 3 year period 1995–97:

13 brain or other central nervous system (CNS) tissue cases (about three expected) and two neuroblastomas (about one expected). In conducting its case–control study, FDOH expanded coverage to include all such cases diagnosed over the 17 year period 1981–97 (29 cases, 21 expected; 22 brain and other CNS cancers, 16.1 expected; and 7 neuroblastomas, 4.9 expected) (FDOH 2001).

While the 15 recent cases (1995–97) represent a significant case cluster in statistical terms, at least for brain and other CNS tumours, the cluster's significance in biological terms is uncertain. Biologic significance depends on finding sufficiently convincing evidence that most of the cases in the cancer cluster share the same plausible local biologic cause, whether exposure to carcinogenic chemicals, exposure to radiation, exposure to infectious agents, shared genetic relationships or some combination thereof (Heath 1996). Neither the studies done by the Florida Department of Health nor the radiation studies reported here have produced such evidence, either for the entire 17 years (1981–97) or for the more recent 3 year period. It remains possible, therefore, if not likely, that the 1995–97 excess of cases reflects a random distribution of cases in time and place and not the result of some shared causation. No evidence suggests that the recent cases differed clinically from earlier cases, had a different geographic residential distribution or had different histories of potential exposure to chemicals or radiation. Places of residence reflected the general distribution of population within the county, and none were in neighbourhoods adjoining the nuclear power station. No parents or immediate family members of affected children were employed at the station. No records of unusual releases of radioactive materials from the station were found, and, among recent cases, no clustering by age at diagnosis was seen that might suggest some shared prenatal exposure that might not otherwise have been suspected.

4.3. Population mixing

One hypothesis gaining support for explaining case clusters of childhood leukaemia/lymphoma reported around nuclear installations and elsewhere is the possibility that such cases may occur as a rare response to an unidentified infection whose transmission is facilitated when large numbers of people come together, such as might occur when large industrial complexes are built in rural areas or when there is a substantial immigration of new residents (Kinlen 1997, Doll 1999). This population mixing hypothesis has recently been extended to consider other forms of childhood cancer including neuroblastoma (Dickinson *et al* 2002b). An infectious disease aetiology has also been proposed for neuroblastoma (Dickinson *et al* 2002a, Menegaux *et al* 2004). St Lucie County has experienced considerable growth in population over the last 50 years: from 20 000 residents in 1950 to 39 000 in 1960 to 51 000 in 1970 to 87 000 in 1980 to 150 000 in 1990 to 187 000 in 2000. Although speculative, the significant elevated rate of childhood leukaemia observed prior to 1976 might be due in part to an as yet unidentified infectious agent associated with population mixing prior to or during the construction of the nuclear power station which began operating in 1976. A second nuclear reactor began operating in 1983, but it seems unlikely that the additional in-migration would result in both a slight increase in childhood cancers of the brain and other nervous tissues and a slight decrease in childhood leukaemia.

4.4. Study strengths and limitations

This community cancer mortality study covered a long time frame, over 50 years, which enabled detailed analyses of several specific cancers. Comparisons of cancer rates before and many years after the start-up of the nuclear power station in 1976 could be made. Comparisons

with demographically similar control counties in the state of Florida and with the entire United States were possible. The numbers of total cancer deaths between 1950 and 2000, over 11 000 and 66 000 in St Lucie and control counties, respectively, was such that any differences could be identified, if they were present. The methodology used was the same as that employed by the NCI in a similar, but larger-scale investigation of mortality in counties throughout the United States with nuclear facilities, including electrical utilities, uranium processing plants and weapons production laboratories (Jablon *et al* 1990, 1991).

The number of childhood cancer deaths, 57 in St Lucie and 354 in the comparison counties, however, was not large but was sufficient to exclude RRs of 1.42 or higher with 95% confidence. For the period 1976–2000, RRs of 1.76, 2.06 and 1.49 or higher for deaths due to childhood leukaemia, brain and other nervous tissue, and all childhood cancers, respectively, could be excluded with 95% confidence. Further, our five-year age-adjusted mortality rate analyses compared the patterns of childhood cancer over time and found no measurable difference between St Lucie County and the comparison counties (figure 2). Our study could only address mortality, however, and improvements in therapies have greatly increased survival, especially for childhood cancers. These improvements would be expected to be similar for residents in St Lucie and the comparison counties, and the incidence analyses conducted by the Florida Department of Health (FDOH 2001) also did not find significant increases in neuroblastoma, brain or other CNS cancers over the years 1981–97. Neuroblastoma also could not be separated from the 'other cancers of the nervous system' because there were no specific International Classification of Diseases (ICD) mortality codes for neuroblastoma in any of the five ICD classifications used between 1950 and 2000. Our descriptive study is further limited by uncertainties associated with migration and with the absence of information on actual exposure, if any, to individuals. Migration might be less of a problem for studies of children, however, given that the time between potential exposure and death would be limited and might not be as great as for adults. Finally, the allowable releases of radiation from a normally operating nuclear facility would be expected to be so low (CFR 2005) that any population study would have low statistical power to detect any effect had there been one.

This study relied on mortality data. Although the accuracy of the cause of death information on death certificates is variable, this inaccuracy is less for cancer than other causes even during the early years of this study (Percy *et al* 1981). Further, the quality of death certificate information would be expected to be similar for St Lucie County and the neighbouring counties which comprised the comparison population. Nonetheless, mortality data are not optimal for monitoring cancers for which improved therapy has markedly lowered death rates in recent years while not affecting incidence. Mortality and incidence rates are highly correlated, however, so that the reliance on mortality data is more of an issue of statistical power than of study bias. In this particular circumstance, cancer incidence data were not available over the time period of interest, and mortality data could address changes in rates before and after the operation of the nuclear power station began.

Data for the calendar years of interest were available only for the entire county and some residents lived up to about 25 miles from the nuclear power station (figure 1), although most of the county population resides within 10 miles. Local effects, nonetheless, would be difficult to detect using county death rates because of any dilution resulting from the inclusion of the populations living at some distance from reactor. Wind direction would also influence the exposure pattern of the population. On the other hand, the increase in brain cancer and other cancers of the nervous tissue was reported for the entire county. Finally, the annual age-specific population estimates in 1950–69 for counties that had much in- or out-migration may be in error as a result of the linear interpolation used for those years, but since broad categories (1950–76 and 1977–2000) were used in the analysis, these errors are likely to be minimal.

5. Conclusion

A mortality study of childhood (and all-age) cancer over the years 1950–2000 failed to identify any increasing patterns of risk in St Lucie County compared with two other similar counties in Florida. Rates before 1976, when the St Lucie nuclear power station began operation, were generally higher than rates after 1976, especially for childhood leukaemia. Childhood brain and other nervous tissue cancer rates were similar over the entire study period and slightly lower than those in the comparison counties. Similar to larger scale studies conducted around all nuclear facilities in the United States, this extended series finds no evidence that living in a community near a nuclear reactor has increased the occurrence of childhood cancer. Limitations of descriptive studies include, however, the possible influence of migration, the absence of knowledge on exposure to individuals, and the inability to adjust for confounding factors among individuals.

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References

ATSDR 1998 *Health Consultation.* Exposure Investigation and Consultation Branch, Division of Health Assessment and Consultation, Agency for Toxic Substances and Disease Registry (http://www.atsdr.cdc.gov/HAC/PHA/stlucie/stl_toc.html#toc)

Bithell J F and Stewart A M 1975 Pre-natal irradiation and childhood malignancy: a review of British data from the Oxford survey *Br. J. Cancer* **31** 271–87

Boice J D Jr, Bigbee W L, Mumma M T and Blot W J 2003a Cancer mortality in counties near two former nuclear materials processing facilities in Pennsylvania, 1950–1995 *Health Phys.* **85** 691–700

Boice J D Jr, Mumma M, Schweitzer S and Blot W J 2003b Cancer mortality in a Texas county with prior uranium mining and milling activities 1950–2001 *J. Radiol. Prot.* **23** 247–62

Breslow N and Day N 1987 *Statistical Methods in Cancer Research* (*IARC Scientific Publication 82* vol 2) (Lyon: IARC)

Code of Federal Regulations (CFR) 2005 *10CFR 20. Title 10–Energy. Part 20: Standards for Protection Against Radiation* http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/

Darby S C and Doll R 1987 Fallout, radiation doses near Dounreay, and childhood leukaemia *Br. Med. J.* **294** 603–7

Dickinson H O, Nyari T A and Parker L 2002a Childhood solid tumours in relation to infections in the community in Cumbria during pregnancy and around the time of birth *Br. J. Cancer* **87** 746–50

Dickinson H O, Parker L, Salotti J and Birch P 2002b Paternal preconceptional irradiation, population mixing and solid tumors in the children of radiation workers (England) *Cancer Causes Control* **13** 183–9

Doll R 1999 The seascale cluster: a probable explanation *Br. J. Cancer* **81** 3–5

FDOH (Florida Department of Health) 2001 *Cancer Risks and Environmental Exposures in St Lucie County Florida (January 1999) and Report to Community* http://www.stluciecountyhealth.com/cancer/slcinterimrpt.pdf (http://www.stluciecountyhealth.com/cancer/report.pdf)

Gould J M, Sternglass E J, Sherman J D, Brown J, McDonnell W and Mangano J J 2000 Strontium-90 in deciduous teeth as a factor in early childhood cancer *Int. J. Health Serv.* **30** 515–39

Heath C W Jr 1996 Investigating causation in cancer clusters *Radiat. Environ. Biophys.* **35** 133–6

IARC 2000 IARC monographs on the evaluation of carcinogenic risks to humans *Ionizing Radiation, Part 1. X-and Gamma* (γ) *Radiation, and Neutrons* vol 75 (Lyon: IARC)

IARC 2001 IARC monographs on the evaluation of carcinogenic risks to humans *Ionizing Radiation, Part 2. Some Internally Deposited Radionuclides* vol 78 (Lyon: IARC)

ICRP (International Commission on Radiological Protection) 1995 Age-dependent doses to members of the public from intake of radionuclides Part 4. Inhalation Dose Coefficients *ICRP Publication 71 (Ann. ICRP* ***25*** *3–4)* (Oxford: Pergamon)

Jablon S, Hrubec Z and Boice J D Jr 1991 Cancer in populations living near nuclear facilities. A survey of mortality nationwide and incidence in two states *JAMA* **265** 1403–8

Jablon S, Hrubec Z, Boice J D Jr and Stone B J 1990 *Cancer in Populations Living Near Nuclear Facilities (NIH Publ. 90-874)* (Washington, DC: US Government Printing Office)

Kinlen L J 1997 Infection and childhood leukaemia near nuclear sites *Lancet* **7** 1702

Mangano J J, Gould J M, Sternglass E J, Sherman J D and McDonnell W 2003 An unexpected rise in strontium-90 in US deciduous teeth in the 1990s *Sci. Total Environ.* **317** 37–51

Mantel N and Ederer F 1985 Exact limits for the ratio of two SMR values *J. Epidemiol. Community Health* **39** 367–8

Mark P 2003 *Suit Alleges Cancer Link to Nuclear Plant. (Fort Pierce Tribune, 2003)*

Marsh G M, Youk A O, Stone R A, Sefcik S and Alcorn 1998 C OCMAP-PLUS: a program for the comprehensive analysis of occupational cohort data *J. Occup. Environ. Med.* **40** 351–62

Menegaux F, Olshan A F, Neglia J P, Pollock B H and Bondy M L 2004 Day care, childhood infections, and risk of neuroblastoma *Am. J. Epidemiol.* **159** 843–51

Monson R R and MacMahon B 1984 Prenatal x-ray exposure and cancer in children *Radiation Carcinogenesis: Epidemiology and Biological Significance* ed J D Boice Jr and J F Fraumeni Jr (New York: Raven) pp 97–105

NCI (National Cancer Institute) 2003 *RateCalc Mortality Rate Generator, Version 3.6 Users Guide* (Bethesda, MD: Division of Cancer Epidemiology and Genetics)

NRC (Nuclear Regulatory Commission) 2001 March 21, 2001 documents regarding "Tooth Fairy Radiation Claims": Letter from New Jersey Department of Environmental Protection to US Nuclear Regulatory Commission. Letter from US Nuclear Regulatory Commission to New Jersey Department of Environmental Protection. US Nuclear Regulatory Commission, Enclosure 1: Issues Raised By Gould, et al. US Nuclear Regulatory Commission, Enclosure 2: Talking Points. US Nuclear Regulatory Commission, Enclosure 3: Strontium http://www.nei.org/index.asp?catnum=4&catid=329

Percy C, Stanek E 3rd and Gloeckler L 1981 Accuracy of cancer death certificates and its effect on cancer mortality statistics *Am. J. Public Health* **71** 242–50

Riggan W B, van Brugen J, Acquavella J F, Beaubier J and Mason T J 1983 *US Cancer Mortality Rates and Trends, 1950–1979* (Washington, DC: US Government Printing Office)

Steenland K, Henley J, Calle E and Thun M 2004 Individual-and area-level socioeconomic status variables as predictors of mortality in a cohort of 179,383 persons *Am. J. Epidemiol.* **159** 1047–56

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000 *Report to the General Assembly, with Scientific Annexes* (New York: UNSCEAR)

USDC (US Department of Commerce) 1992 *Census of Population and Housing, 1990: Summary Tape File 3 on CD-ROM [Machine-Readable Data Files]* (Washington: The Bureau) (prepared by the Bureau of the Census)

Paper

CANCER MORTALITY AMONG POPULATIONS RESIDING IN COUNTIES NEAR THE HANFORD SITE, 1950–2000

John D. Boice, Jr.,*† Michael T. Mumma,* and William J. Blot*†

Abstract—**A descriptive epidemiologic study of cancer mortality among residents of counties near the Hanford nuclear facility site in Richland, Washington, was conducted. Between 1944 and 1957, radioactive ^{131}I was released into the environment from the Hanford site. Cancer mortality from 1950 through 2000 was evaluated in four counties with the highest estimated exposure to ^{131}I and compared with the cancer mortality experience in five demographically similar counties in Washington State with minimal ^{131}I exposure. Overall, cancer rates in the study counties were slightly below those in the comparison counties [relative risk (RR) 0.95; 95% confidence interval (CI) 0.93–0.97], due mainly to a low risk for lung cancer (RR 0.89; 95% CI 0.85–0.93). Thyroid cancer (*n* = 33; RR 0.84; 95% CI 0.56–1.26), female breast cancer (*n* = 1,233; RR 0.99; 95% CI 0.92–1.06), leukemia other than chronic lymphocytic leukemia (*n* = 492; RR 0.95; 95% CI 0.85–1.06), and childhood leukemia (*n* = 71; RR = 1.06; 95% CI 0.78–1.43) were not significantly increased in the exposed counties. Furthermore, there was no evidence that the cancer death rates over time differed between study and comparison counties. Patterns over time of thyroid cancer in particular were similar for exposure and comparison counties. Although based on a geographic correlation design, these data suggest that living near the Hanford site has not increased cancer rates.**

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Key words: cancer; Hanford accident; exposure, population; mortality

INTRODUCTION

THE HANFORD nuclear facility began operation in 1943 in Richland, Washington. Activities have included the operation of reactors to produce nuclear materials, the reprocessing of fuel to recover plutonium and uranium, and the production of plutonium for the United States nuclear weapons program (Farris et al. 1996; Napier 2002). Between 1944 and 1957 airborne releases of ^{131}I occurred.

Herein we report on mortality among residents in counties near the Hanford installation. The current survey extends by 16 years a previous one conducted by the National Cancer Institute (NCI) that evaluated the cancer mortality experience of residents near nuclear facilities in the United States, including the Hanford Production Operation over the years 1950 through 1984 (Jablon et al. 1990). The initial NCI survey was conducted in response to reports from the United Kingdom that childhood leukemia rates might be elevated in areas near nuclear installations. These reports were not confirmed in the United States (Jablon et al. 1991) or in other countries (UNSCEAR 1994). However, in the 1940's through the 1950's, radioactive iodine, specifically ^{131}I, was released from the Hanford site into the environment, and concerns over possible health effects were raised. A large-scale epidemiologic study of persons potentially exposed to ^{131}I as children was conducted in response to these concerns (NRC 2000; Davis et al. 2002, 2004a). The survey reported here looks at the cancer mortality experience of all residents in counties near the Hanford facility over the years 1950–2000.

METHODS

The current survey used somewhat different criteria to select study and comparison counties than in the previous NCI survey (Jablon et al. 1990). Four counties with the highest exposure to ^{131}I were chosen as study counties based on extensive reports on release patterns and wind direction that became available after the NCI study was completed (Farris et al. 1994, 1996; Napier 2002). Five comparison counties were chosen based on an algorithm that took into account population and demographic characteristics, after excluding counties with potential for moderate exposure to ^{131}I. The previous NCI survey had selected three exposure counties and three control counties and used geographic proximity to the Hanford site as the primary consideration for selection. The previous NCI survey reported no significant

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elevations in childhood leukemia, thyroid cancer, or any other cancer over the years 1950–1984 (Jablon et al. 1990).

The same methodology, computer programs, and databases used by the earlier NCI investigation (Jablon et al. 1990) were used in this extended Hanford mortality survey. Similar methodologic approaches also have been used to evaluate cancer mortality in communities living in areas of increased radiation from mining, milling and uranium processing operations (Boice et al. 2003a and b).

Cancers considered in the study

Because radioactive iodine is efficiently absorbed by the thyroid gland, thyroid cancer is the major outcome of interest. To the extent that any plutonium or uranium was released into the environment, the following kinds of cancer would be of interest based on the likely deposition in body tissue: cancers of the lung, bone, liver, and kidney (IARC 2001). In addition, based on knowledge of cancers found increased after high dose and high dose rate external exposures to gamma or x rays, cancers of the stomach, colon, brain, female breast, and leukemia were studied (Boice 2006a; UNSCEAR 2000; IARC 2000). For completion, other cancers were included, including those not frequently found to be increased in exposed populations such as cancers of the esophagus, pancreas, cervix uteri and corpus uteri, prostate, malignant melanoma of the skin, Hodgkin's disease, non-Hodgkin's lymphoma, and multiple myeloma. Because children are somewhat more sensitive to the late effects of ionizing radiation (Preston et al. 2003), childhood leukemia and all childhood cancers occurring under the age of 15 y were also evaluated.

Mortality data

Cancer mortality data for all counties in the state of Washington were available from the National Cancer Institute from 1950–2000 (NCI 2003). Counties are the smallest areas for which both population estimates and annual counts of the number of deaths for specific causes are readily available back to 1950 from the National Center for Health Statistics and the U.S. Census Bureau (NCI 2003).

Selection of exposure and comparison counties

The procedural steps to determine exposure and comparison counties were as follows:

1. All 119 counties in the states of Washington, Oregon, and Idaho were initially considered eligible for selection as comparison and exposure counties;
2. An exposure assessment score was assigned to the 30 counties surrounding the Hanford site based on the relative geographic distribution of the estimated level of ^{131}I and the cumulative thyroid dose to a theoretical population of children residing within each county (Farris et al. 1994, 1996; Napier 2002). These estimates took into account wind direction, soil deposition and possible milk consumption patterns. The four counties with the highest exposure score were considered "study" counties (Benton, Adams, Franklin, and Walla Walla). These four counties were also chosen as having the highest potential exposure to ^{131}I in a recent epidemiologic study (Davis et al. 2004a). Counties with moderate exposure scores (Lincoln, Spokane, Whitman, Columbia, Pend Oreille, Stevens, Umatilla, Grant, Morrow) or counties that were immediately adjacent to the Hanford site (Yakima) were excluded from consideration as comparison counties;
3. Census Bureau (USDC 1992) demographic data for 1990 on the following nine socio-economic variables were obtained for the four exposure and all remaining 105 potential comparison counties: population density (total persons divided by county area), percent male, percent white, percent rural, percent high school graduate, percent aged 65+ years, percent employed, percent below poverty and median household income; and
4. For each demographic characteristic, a score of 0, 1, or 2 was assigned based on the similarity to the weighted mean value of the four exposure counties with the weights taken as the county populations. A score of 2 indicated close agreement with the study counties average and a score of 0 indicated a lack of similarity with the study counties. Although there was some subjectivity in assigning scores, category boundaries were chosen to best discriminate between counties that were similar on demographic and socio-economic factors from those that were dissimilar. Specifically, scores and boundaries were assigned as detailed below.

Population density (exposure counties = 49.6 persons/sq mile).

- 0 if >100 persons/sq mile or <7 persons/sq mile
- 1 if 7–30 or 30–100 persons/sq mile
- 2 if 30–70 persons/sq mile

Percent male (exposure counties = 50.2% male).

- 0 if >55% or <45%
- 1 if 45–49.5% or 52–55%
- 2 if 49.5–52%

Percent white (exposure counties = 96% white).

- 0 if <90% white

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- 1 if 90–93% white or >97%
- 2 if 93–97% white

Percent rural (exposure counties = 22% rural).

- 0 if <10% or >85%
- 1 if 10–25 or 75–85%
- 2 if 25–75%

Percent high school graduate (exposure counties = 79%).

- 0 if <65% or >90%
- 1 if 65–70 or 85–90%
- 2 if 70–85%

Percent over age 65 years (exposure counties = 11%).

- 0 if <5% or >20%
- 1 if 5–9% or 16–20%
- 2 if 9–16%

Percent employed (exposure counties = 61%).

- 0 if <45% or >70%
- 1 if 45–55%, or 65–70%
- 2 if 55–65%

Percent below poverty (exposure counties = 14%).

- 0 if <5% or >30%
- 1 if 5–11% or 23–30%
- 2 if 11–23%

Median household income (exposure counties = $28,800).

- 0 if >$37,000 or <$20,000
- 1 if $20,000–$23,999 or $33,001–$37,000
- 2 if $24,000–$33,000

Geographic proximity to Hanford site.

- 0 if greater than 150 miles
- 1 if >50 miles, but within 150 miles
- 2 if within 50 miles

Data on diet, smoking, and other potential cancer risk factors are not readily available at the county level, but choosing comparison counties from the same region as the study counties helps minimize differences in these and other factors. Accordingly, an additional two points were added for counties within the state of Washington. The assigned scores for each demographic characteristic were then summed for each county. Table 1 shows the rankings of counties in Washington state; scores for all counties in Oregon and Idaho were computed but not presented since they were lower than the five counties in Washington state selected for comparison. The five counties with the highest similarity scores (Douglas, Skagit, Chelan, Kittitas, and Whatcom) were selected as comparison counties (Fig. 1). The determination of a socio-economic score based on area-level characteristics is similar to that done in other studies (Steenland et al. 2004).

Statistical analyses

Analyses were based on the underlying cause of death, coded according to the ninth revision of the International Classification of Diseases (ICD) (WHO 1977). Counts of cancer deaths by site, sex, race, and 5-y age group were obtained for each of the five selected counties for each year from 1950 to 2000. Estimated annual county populations by sex, race, and age group were obtained by interpolation in census counts for 1950 to 1969, and for later years decennial censuses were prepared by the Bureau of the Census (Jablon et al. 1990; NCI 2003). For each type of cancer and each county the "expected" numbers of deaths, based on concurrent U.S. experience, were calculated for the 51-y study period (Marsh et al. 1998; NCI 2003). The expected numbers were obtained by multiplying annual U.S. cancer death rates by the estimated populations, stratified by 5-y age group and sex. Counts were then summed for the four study counties and for all five of the comparison counties. Counts of observed and expected deaths were then summed over the following time periods: 1950–1964 (just after and during the period of major ^{131}I releases from Hanford), 1965–1979, 1980–1989, and 1990–2000. The minimum latency period for the development of solid cancer following radiation exposure is about 5 to 10 y and for leukemia about 2 y (IARC 2000). Thus, there was ample opportunity for residents in the exposure counties to accumulate dose and for trends in cancer rates to be evaluated. This approach is the same as what was done previously by the National Cancer Institute (NCI) using similar databases and statistical programs (Jablon et al. 1990).

The ratio of the actual number of deaths observed to the number expected at U.S. rates is the standardized mortality ratio (SMR). Ratios of the standardized mortality ratios for the study to the comparison counties were called "relative risks" (RRs) although this is not the traditional usage of the term *relative risk*. Ninety-five percent confidence intervals (CIs) were calculated for each RR following the method described in the NCI study (Mantel and Ederer 1985; Breslow and Day 1987; Jablon et al. 1990). A 95% CI that contains 1.00 indicates that chance cannot be ruled out as an explanation for any observed differences in cancer mortality rates between study counties and the comparison counties.

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Table 1. Ranking of Washington counties based on an algorithm of demographic and socio-economic characteristics[a] used to select comparison counties that are similar to the four ^{131}I exposure study counties.

County	Total score	Total persons	Popn density	Percent Male	White	White other	Rural	HS Grad+	Age 65+	Employed	Below poverty	Med HH income ($)
Exposure Counties												
Walla Walla	22	48,439	38.1	50.8	89.5	96.6	26.2	78.5	15.7	56.1	14.7	24,414
Franklin	21	37,473	30.2	51.6	72.0	93.5	27.3	65.5	9.8	60.8	22.7	24,604
Benton	20	112,560	66.1	49.5	91.5	96.4	12.8	82.0	10.1	63.8	11.0	32,593
Adams	18	13,603	7.1	50.7	66.9	98.7	65.9	64.0	11.2	62.1	17.3	24,604
All Study Counties		212,075	49.6	50.2	86.0	96.1	21.8	79.1	11.4	61.4	14.3	28,800
Selected Comparison Counties												
Douglas	20	26,205	14.4	50.5	92.4	98.1	41.8	73.9	12.1	60.0	12.1	27,054
Skagit	20	79,555	45.8	49.4	93.2	96.6	50.4	79.9	15.7	56.4	11.3	28,389
Chelan	19	52,250	17.9	49.2	92.6	98.1	47.7	73.1	15.7	58.3	15.0	24,312
Kittitas	19	26,725	11.6	49.6	95.6	97.1	53.7	84.5	13.3	55.0	18.4	20,489
Whatcom	19	127,780	60.3	49.5	93.5	94.6	40.8	83.7	12.7	62.2	11.9	28,367
All Selected Control Counties		312,515	41.5	49.5	93.4	96.2	45.6	80.3	14.0	59.3	13.0	25,760
Nonselected counties												
Cowlitz	18	82,119	72.1	49.5	95.2	96.3	30.2	76.3	13.5	55.4	13.1	27,866
Grays Harbor	18	64,175	33.5	49.8	94.0	94.6	46.6	73.0	15.9	50.3	16.1	23,042
Clallam	17	56,464	32.4	49.8	93.0	93.4	52.5	78.5	20.4	47.8	12.1	25,434
Klickitat	17	16,616	8.9	50.3	92.5	95.5	80.0	68.9	14.1	52.6	16.8	23,012
Lewis	17	59,358	24.7	49.3	96.9	97.4	68.3	74.5	15.7	52.9	14.1	24,410
Mason	17	38,341	39.9	51.6	93.4	94.0	81.1	77.3	16.5	48.2	12.6	26,304
Asotin	15	17,605	27.7	47.3	97.9	98.3	23.3	76.7	16.6	53.7	18.9	22,897
Clark	15	238,053	379.1	49.4	94.8	95.5	22.3	82.5	10.7	62.7	9.2	31,800
Jefferson	15	20,146	11.1	49.3	95.4	95.4	51.6	81.4	20.7	47.9	13.3	25,197
Kitsap	15	189,731	479.1	51.0	90.1	91.2	34.7	85.6	10.7	63.1	9.0	32,043
Pierce	15	586,203	349.9	50.0	85.2	86.4	12.7	82.5	10.4	62.5	10.9	30,412
Skamania	15	8,289	5.0	51.0	95.6	95.8	100.0	74.6	10.7	54.8	9.3	28,778
Snohomish	15	465,642	222.8	49.8	93.4	94.1	20.4	84.5	9.5	67.9	6.5	36,847
Thurston	15	161,238	221.8	48.7	92.1	93.0	40.8	85.3	11.7	62.6	9.9	30,976
Wahkiakum	15	3,327	12.6	49.7	94.9	96.2	100.0	74.7	19.5	57.1	10.2	26,969
Island	14	60,195	288.6	52.2	91.5	92.5	65.2	87.7	13.8	61.6	6.9	29,161
Okanogan	14	33,350	6.3	50.5	82.7	88.7	87.7	69.6	13.9	55.1	21.2	20,303
Pacific	14	18,882	19.4	49.7	93.0	94.0	84.6	72.9	21.7	46.7	16.8	20,029
Ferry	13	6,295	2.9	52.5	80.9	81.6	100.0	70.7	10.6	50.1	23.6	25,170
Garfield	13	2,248	3.2	49.0	99.2	99.2	100.0	81.5	22.2	56.1	10.3	25,156
King	10	1,507,319	709.0	49.2	84.9	85.9	5.8	87.5	11.1	68.5	7.8	36,179
San Juan	10	10,035	57.4	49.5	97.7	97.8	100.0	90.8	21.3	53.9	7.3	31,278
Washington State		4,866,692		49.6	88.6	90.9	23.6	83.8	11.2	47.1	10.6	31,183

[a] Popn Density denotes population density (persons/square mile); HS Grad denotes high school graduate; Med HH Income denotes median household income.

Strata containing three or fewer cancer deaths are not presented but are listed as LT4 to denote "less than four." This is to abide by the confidentiality requirements for using the NCI and National Center for Health Statistics database. The concern is the possibility that individuals with certain characteristics might be identified if the number of deaths were small.

RESULTS

In 1990, the total number of residents within the four study and five comparison counties were 212,075 and 312,515, respectively (Table 1). The comparison counties were similar to the study counties with regard to demographic indicators of cancer risk such as age, race, and various measures of socio-economic status. Over 85% of the population studied was White, with a small percentage of Black or Asian; 11–13% of the county residences were older than 64 y; over 79% had graduated from high school; and 61% were employed. The median household income in 1989, about $26,000 to $28,000 per year, was also similar between the study and comparison county populations. Comparison counties were more rural (46% vs. 22%) than the study counties but were similar with regard to poverty level (13% vs. 14%). The study and comparison counties were slightly less affluent than the state of Washington.

Table 2 presents the total number of observed and expected cancer deaths, overall and for specific cancers, occurring during 1950–2000 within the four ^{131}I exposed

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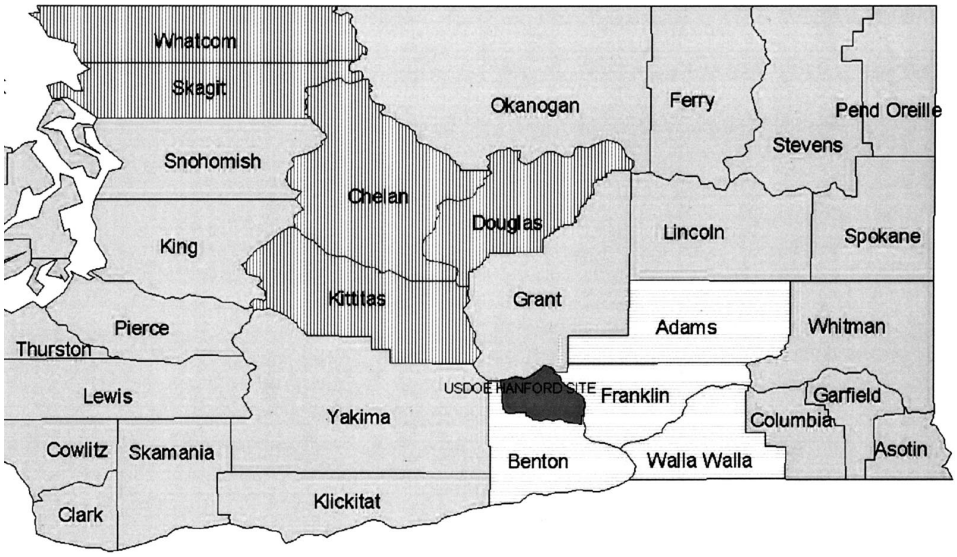

Fig. 1. County map of Washington State indicating the four study counties (Benton, Franklin, Adams, Walla Walla) most heavily exposed to ^{131}I releases from the Hanford site and the five demographically similar comparison counties (Kittitas, Chelan, Douglas, Skagit, Whatcom).

Table 2. Observed (obs) and expected (exp)[a] numbers of cancer deaths and SMRs occurring in the four ^{131}I exposed study counties and in the five comparison counties during 1950–2000.

	Study Counties			Comparison Counties		
Cancer (ICD9)[b]	Obs	Exp	SMR	Obs	Exp	SMR
Esophagus (150)	221	282.9	0.78	478	548.3	0.87
Stomach (151)	469	636.7	0.74	1,061	1,278.6	0.83
Colon/rectum (153, 154)	1,678	2,018.9	0.83	3,303	3,960.0	0.83
Pancreas (157)	799	806.3	0.99	1,575	1,569.1	1.00
Lung (162)	3,261	3,797.0	0.86	7,024	7,279.8	0.96
Melanoma/skin (172)	74	84.7	0.87	133	167.5	0.79
Female breast (174)	1,245	1,356.7	0.92	2,308	2,487.5	0.93
Cervix uteri (180)	176	219.0	0.80	355	395.8	0.90
Corpus uteri (182)	223	224.7	0.99	406	430.5	0.94
Ovary (183)	411	430.5	0.95	852	797.5	1.07
Prostate (185)	904	885.8	1.02	1,933	1,871.6	1.03
Urinary bladder (188)	314	394.8	0.80	732	801.2	0.91
Kidney/renal pelvis (189)	329	328.2	1.00	603	626.3	0.96
Liver and kidney (155, 189)	523	537.2	0.97	926	1,023.0	0.91
Bone (170)	66	68.4	0.96	104	120.8	0.86
Connective tissue (171)	85	92.9	0.91	161	165.0	0.98
Brain and CNS (191, 192)	453	410.8	1.10	800	722.8	1.11
Thyroid (193)	33	42.3	0.78	76	81.8	0.93
Non-Hodgkin's lymphoma (200, 202)	533	564.0	0.95	1,058	1,060.0	1.00
Hodgkin's disease (201)	79	109.7	0.72	161	185.2	0.87
Multiple myeloma (203)	232	230.7	1.01	451	447.3	1.01
Leukemia (204–208)	646	689.9	0.94	1,202	1,275.9	0.94
Leukemia, CLL[c]	153	142.9	1.07	262	282.2	0.93
Leukemia, not CLL	492	546.2	0.90	940	992.2	0.95
Childhood leukemia (<15 y)	71	61.2	1.16	103	93.7	1.10
Childhood cancer (<15 y)	145	139.5	1.04	227	213.0	1.07
All cancers (140–208)	14,143	16,042.6	0.88	28,567	30,791.8	0.93

[a] Expected numbers based on U.S. rates.
[b] WHO (1977).
[c] CLL denotes chronic lymphocytic leukemia.

counties and the five comparison counties. There were 14,143 cancer deaths in the study counties and 28,567 cancer deaths in the comparison counties. The most frequent causes of death were cancer of the lung, female breast, colon and rectum, and male prostate. Death from thyroid cancer was relatively infrequent with 33 and 76

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deaths in the study and comparison counties, respectively. The numbers of childhood leukemia deaths were 71 in the study counties and 103 in the comparison counties. The SMRs for study and comparison counties were similar (Table 2). Compared with the general population of the United States, SMRs were close to or below 1.0 for most cancer sites. When increased SMRs were observed, e.g., for cancers of the prostate and brain and childhood cancer, the elevations were seen in both study and comparison counties.

Table 3 presents, for females, the relative risks of mortality for selected cancers in the ^{131}I exposure counties compared to the minimally exposed comparison counties for four time periods during 1950–2000. Overall, female cancer rates in the study counties were slightly below those in the comparison counties (RR 0.94; 95% CI 0.92–0.97), mainly related to a low risk for lung cancer (RR 0.86; 95% CI 0.80–0.93). No cancer was significantly elevated. The most frequent cause of cancer death was female breast cancer (n = 1,233; RR 0.99; 95% CI 0.92–1.06). Thyroid cancer (RR 0.71; 95% CI 0.41–1.21), leukemia other than chronic lymphocytic leukemia (RR 0.93; 95% CI 0.79–1.10), and childhood leukemia (RR 0.75; 95% CI 0.46–1.24) were not increased. There were no increasing trends over time for any cancer.

Table 4 presents, for males, the relative risks of mortality for selected cancers in the ^{131}I exposure counties compared to the minimally exposed comparison counties for four time periods during 1950–2000. Similar to the patterns seen for females, the overall male cancer rates in the study counties were slightly below those in the comparison counties [RR 0.95; 95% CI 0.93–0.98] related to a low risk for lung cancer (RR 0.90; 95% CI 0.86–0.95). No other cancer was significantly above or below expectation. The most frequent cancer death was lung cancer (n = 2,235). Thyroid cancer (RR 1.09; 95% CI 0.58–2.04), leukemia other than chronic lymphocytic leukemia (RR 0.96; 95% CI 0.83–1.11), and childhood leukemia (RR 1.31; 95% CI 0.89–1.93) were not significantly increased. Bone cancer among males was increased but not significantly (RR 1.43; 95% CI 0.96–2.14). In contrast, bone cancer among females was decreased but not significantly (RR 0.80; 95% CI 0.49–1.30). There were no increasing trends in the RR over time for males residing in the study counties compared to

Table 3. Relative risks of mortality due to selected cancers in the four ^{131}I exposed study counties contrasted with the five comparison counties for four time periods during 1950–2000 in Washington State for females.

	1950–64		1965–79		1980–89		1990–2000		All years 1950–2000		95% CI	
Cancer (ICD9)[a]	Obs[b]	RR	Obs	RR	Obs	RR	Obs	RR	Obs	RR	Lower	Upper
Esophagus (150)	4	0.52	9	0.59	13	1.13	26	0.95	52	0.84	0.61	1.17
Stomach (151)	54	0.89	55	1.00	35	1.10	25	0.66	169	0.91	0.76	1.09
Colon/rectum (153, 154)	159	1.12	249	1.11	170	0.74	246	0.97	824	0.98	0.90	1.06
Pancreas (157)	56	1.27	82	0.95	93	0.86	139	0.90	370	0.95	0.83	1.07
Lung (162)	35	0.92	157	0.88	287	0.85	547	0.86	1,026	0.86	0.80	0.93
Skin/melanoma (172)	7	1.24	7	1.43	LT4	0.23	11	1.22	26	1.09	0.67	1.76
Female breast (174)	177	0.85	345	0.99	317	1.02	394	1.03	1,233	0.99	0.92	1.06
Cervix uteri (180)	65	0.91	54	1.03	26	0.93	31	0.70	176	0.90	0.75	1.07
Uterus (182)	45	0.87	66	1.17	54	1.12	58	1.04	223	1.05	0.89	1.24
Ovary (183)	71	1.04	111	0.91	98	0.99	131	0.77	411	0.89	0.79	1.01
Bladder (188)	9	0.45	42	1.79	16	0.60	24	0.78	91	0.90	0.70	1.16
Kidney (189)	16	1.28	23	0.88	24	0.73	46	1.00	109	0.93	0.74	1.17
Liver and kidney (155, 189)	16	1.28	41	0.97	47	0.94	89	1.12	193	1.05	0.88	1.25
Bone (170)	7	0.58	8	1.05	5	2.03	LT4	0.47	23	0.80	0.49	1.30
Connective tissue (171)	LT4	0.75	6	0.94	13	1.11	14	0.74	35	0.88	0.59	1.33
Brain and CNS (191, 192)	16	0.58	49	1.05	48	1.05	68	1.04	181	0.97	0.81	1.17
Thyroid (193)	5	0.69	LT4	0.19	6	0.84	6	1.03	18	0.71	0.41	1.21
NHL (200, 202)	30	1.22	59	1.13	70	1.08	89	0.80	248	0.98	0.84	1.14
Hodgkin's disease (201)	14	1.39	LT4	0.24	10	2.72	4	0.64	31	0.95	0.61	1.47
Multiple myeloma (203)	12	1.53	29	1.21	36	1.58	30	0.58	107	1.01	0.80	1.28
Leukemia (204–208)	49	0.89	79	1.19	55	0.87	86	0.97	269	0.98	0.85	1.14
Leukemia, CLL	16	0.97	14	1.55	12	2.47	14	0.93	56	1.23	0.88	1.71
Leukemia, not CLL	33	0.86	65	1.13	43	0.73	72	0.98	213	0.93	0.79	1.10
Childhood leukemia (<15 y)	10	0.69	10	0.89	LT4	1.42	LT4	0.30	23	0.75	0.46	1.24
Childhood cancer (<15 y)	22	0.85	18	0.88	7	1.10	4	0.43	51	0.82	0.58	1.15
All (140–208)	967	0.93	1,650	1.01	1,604	0.95	2,271	0.90	6,492	0.94	0.92	0.97

[a] WHO (1977).
[b] Observed number of cancer deaths in study counties. LT4 denotes less than 4 deaths.

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Table 4. Relative risks of mortality due to selected cancers in the four ^{131}I exposed study counties contrasted with the five comparison counties for four time periods during 1950–2000 in Washington State for males.

	1950–64		1965–79		1980–89		1990–2000		All years 1950–2000		95% CI	
Cancer (ICD9)[a]	Obs[b]	RR	Obs	RR	Obs	RR	Obs	RR	Obs	RR	Lower	Upper
Esophagus (150)	25	1.09	33	0.84	49	1.27	62	0.73	169	0.91	0.76	1.10
Stomach (151)	111	0.90	85	0.95	53	0.84	51	0.77	300	0.88	0.77	1.00
Colon/rectum (153, 154)	154	0.94	221	1.01	205	0.97	274	1.11	854	1.02	0.94	1.10
Pancreas (157)	69	0.90	138	1.09	88	0.92	134	1.12	429	1.02	0.91	1.15
Lung (162)	245	1.00	575	0.85	592	0.82	823	0.97	2,235	0.90	0.86	0.95
Skin/melanoma (172)	11	0.98	15	1.87	8	0.73	14	1.06	48	1.11	0.78	1.57
Breast (174)	LT4	1.27	4	1.93	LT4	2.83	LT4	0.79	12	1.48	0.70	3.13
Prostate (185)	130	0.91	232	1.08	217	0.95	325	0.99	904	0.99	0.91	1.07
Bladder (188)	47	0.87	58	0.77	44	0.71	74	1.07	223	0.86	0.73	1.00
Kidney (189)	43	1.28	59	1.48	40	0.73	78	1.10	220	1.11	0.94	1.31
Liver and kidney (155, 189)	43	1.28	74	1.09	72	0.95	141	1.13	330	1.09	0.95	1.25
Bone (170)	14	1.43	15	1.70	5	0.71	9	1.95	43	1.43	0.96	2.14
Connective tissue (171)	4	0.94	9	0.83	13	0.88	24	1.13	50	0.98	0.69	1.38
Brain and CNS (191, 192)	45	0.91	69	1.00	72	1.29	86	0.92	272	1.01	0.87	1.17
Thyroid (193)	5	1.16	7	4.45	LT4	0.92	LT4	0.18	15	1.09	0.58	2.04
NHL (200, 202)	38	0.85	73	0.96	69	0.99	105	0.87	285	0.92	0.80	1.06
Hodgkin's disease (201)	20	0.87	13	0.53	10	1.75	5	0.54	48	0.76	0.54	1.08
Multiple myeloma (203)	12	1.19	26	1.03	31	0.70	56	1.17	125	0.99	0.80	1.22
Leukemia (204–208)	85	1.08	98	0.90	82	1.04	112	1.01	377	1.00	0.88	1.14
Leukemia, CLL	44	1.57	13	0.73	12	1.06	28	0.96	97	1.12	0.87	1.43
Leukemia, not CLL	41	0.81	85	0.94	69	1.02	84	1.04	279	0.96	0.83	1.11
Childhood leukemia (<15 y)	25	1.12	13	1.52	6	1.70	4	2.03	48	1.31	0.89	1.93
Childhood cancer (<15 y)	40	1.00	28	1.12	16	1.33	10	1.08	94	1.09	0.83	1.42
All (140–208)	1,244	0.98	2,007	0.96	1,828	0.91	2,572	0.97	7,651	0.95	0.93	0.98

[a] WHO (1977).
[b] Observed number of cancer deaths in study counties. LT4 denotes less than 4 deaths.

Table 5. Relative risks of mortality due to selected cancers in the four ^{131}I exposed study counties contrasted with the five comparison counties for four time periods during 1950–2000 in Washington State for both sexes combined.

	1950–64		1965–79		1980–89		1990–2000		All years 1950–2000		95% CI	
Cancer (ICD9)[a]	Obs[b]	RR	Obs	RR	Obs	RR	Obs	RR	Obs	RR	Lower	Upper
Esophagus (150)	29	0.95	42	0.77	62	1.24	88	0.79	221	0.90	0.76	1.05
Stomach (151)	165	0.89	140	0.97	88	0.93	76	0.73	469	0.89	0.80	0.99
Colon/rectum (153, 154)	313	1.02	470	1.06	375	0.85	520	1.04	1,678	1.00	0.94	1.06
Pancreas (157)	125	1.04	220	1.03	181	0.89	273	1.00	799	0.99	0.91	1.07
Lung (162)	280	0.99	732	0.86	879	0.83	1,370	0.93	3,261	0.89	0.85	0.93
Skin/melanoma (172)	18	1.07	22	1.71	9	0.59	25	1.13	74	1.10	0.83	1.46
Female breast (174)	180	0.85	349	0.99	320	1.02	396	1.03	1,245	0.99	0.92	1.06
Cervix uteri (180)	65	0.91	54	1.03	26	0.93	31	0.7	176	0.90	0.75	1.07
Uterus (182)	45	0.87	66	1.17	54	1.12	58	1.04	223	1.05	0.89	1.24
Ovary (183)	71	1.04	111	0.91	98	0.99	131	0.77	411	0.89	0.79	1.01
Prostate (185)	130	0.91	232	1.08	217	0.95	325	0.99	904	0.99	0.91	1.07
Bladder (188)	56	0.76	100	1.01	60	0.68	98	0.98	314	0.87	0.76	0.99
Kidney (189)	59	1.28	82	1.24	64	0.73	124	1.06	329	1.04	0.91	1.19
Liver and kidney (189, 155)	59	1.28	115	1.04	119	0.95	230	1.13	523	1.08	0.97	1.20
Bone (170)	21	0.96	23	1.40	10	1.06	12	1.10	66	1.12	0.82	1.53
Connective tissue (171)	6	0.87	15	0.87	26	0.98	38	0.95	85	0.94	0.72	1.22
Brain and CNS (191, 192)	61	0.79	118	1.02	120	1.18	154	0.97	453	1.00	0.89	1.12
Thyroid (193)	10	0.87	8	1.16	8	0.86	7	0.61	33	0.84	0.56	1.26
NHL (200, 202)	68	0.98	132	1.03	139	1.03	194	0.84	533	0.95	0.85	1.05
Hodgkin's disease (201)	34	1.03	16	0.43	20	2.13	9	0.58	79	0.83	0.63	1.08
Multiple myeloma (203)	24	1.34	55	1.12	67	1.00	86	0.87	232	1.00	0.85	1.17
Leukemia (204–208)	134	1.00	177	1.01	137	0.97	198	1.00	646	0.99	0.90	1.09
Leukemia, CLL	60	1.35	27	1.00	24	1.48	42	0.94	153	1.15	0.94	1.41
Leukemia, not CLL	74	0.83	150	1.01	112	0.89	156	1.01	492	0.95	0.85	1.06
Childhood leukemia (<15 y)	35	0.95	23	1.16	8	1.62	5	0.95	71	1.06	0.78	1.43
Childhood cancer (<15 y)	62	0.94	46	1.01	23	1.25	14	0.75	145	0.98	0.79	1.20
All (140–208)	2,211	0.96	3,657	0.98	3,432	0.93	4,843	0.94	14,143	0.95	0.93	0.97

[a] WHO (1977).
[a] Observed number of cancer deaths in study counties.

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the comparison counties.

Table 5 presents, for both sexes combined, the relative risks of mortality for selected cancers in the ^{131}I exposure counties compared to the minimally exposed comparison counties for four time periods during 1950–2000. Overall, cancer rates in the study counties were slightly below those in the comparison counties (RR 0.95; 95% CI 0.93–0.97) due to a low risk for lung cancer (RR 0.89; 95% CI 0.85–0.93). Thyroid cancer (n = 33; RR 0.84; 95% CI 0.56–1.26), leukemia other than chronic lymphocytic leukemia (n = 492; RR 0.95; 95% CI 0.85–1.06), and childhood leukemia (n = 71; RR = 1.06; 95% CI 0.78–1.43) were not significantly increased and showed no increasing pattern of risk over the 51-y period of observation. Of the 27 relative risks presented for the total period, 12 were less than 1.00, 8 were close to 1.00, and 7 were greater than 1.00, which is a distribution consistent with the play of chance when making many comparisons.

Fig. 2 presents the age-standardized mortality rates of thyroid cancer for persons residing in the ^{131}I study counties contrasted with the age-standardized mortality rates of thyroid cancer for people residing in the comparison counties from 1950 through 2000. The rates are presented as five-year moving averages to smooth out fluctuations in rates that occur when studying relatively small populations where the number of cases, i.e., thyroid cancers, varies from year to year. There is essentially no divergence in the patterns of thyroid cancer between the study and comparison counties for the 51-y period.

DISCUSSION

Cancer rates among persons living in the counties most heavily exposed to ^{131}I during the Hanford releases in the 1940's and 1950's were not found to be different from the cancer rates in persons living in demographically similar counties in the state of Washington with minimal exposure to ^{131}I. For all cancers taken together and for all specific cancers, there was no evidence of increased cancer rates among residents of counties near the Hanford site. These results are similar to those in the previous study (Jablon et al. 1990) but extend the period of observation by 16 y from 1985 through 2000.

All of the relative risks for specific cancers were close to 1.00, indicating that there was essentially no difference in the mortality experience between persons living in the exposure counties and potentially exposed to ^{131}I during the releases from Hanford and persons living in similar counties in the state of Washington with minimal exposure potential. Only one statistically significant observation, i.e., lung cancer (RR 0.89), was decreased, suggesting that people in the study counties may have been less likely to smoke cigarettes than persons in the comparison counties (although it is generally found that persons residing in more rural than

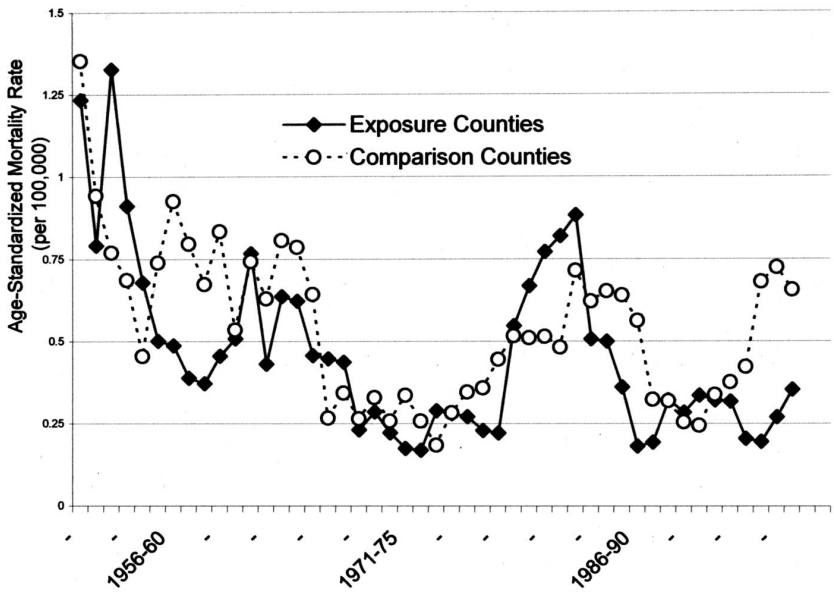

Fig. 2. Age-standardized mortality rates for thyroid cancer for persons residing in the four ^{131}I exposure counties (Benton, Franklin, Adams, Walla Walla) from 1950 through 2000 compared with the five comparison counties (Kittitas, Chelan, Douglas, Skagit, Whatcom). Five-year moving averages are presented to smooth fluctuation in rates due to the relatively small number of thyroid cancers occurring over these years.

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urban areas would smoke less). The overall distribution of relative risks, some slightly high and some slightly low, is as might be expected from the random variations commonly seen in population statistics.

The previous investigation evaluated cancer mortality through 1984 (Jablon et al. 1990). Our extended survey through 2000 did not indicate any material changes in the patterns of risk overall or for specific cancers. The overall relative risks for all cancers (RR 0.96 vs. 0.95), female breast cancer (RR 0.92 vs. 0.99), lung cancer (RR 0.96 vs. 0.89), thyroid cancer (1.17 vs. 0.84), and leukemia (0.92 vs. 0.99) were similar between the former and current surveys.

^{131}I would be expected to deposit most of its energy within the thyroid gland as opposed to other organs. The risk of thyroid cancer was not elevated in the counties most exposed to ^{131}I (RR 0.84; 95% CI 0.56–1.26), and there was no increase in thyroid cancer over time. The age-standardized mortality rates for thyroid cancer were also evaluated from 1950 through 2000 for persons living in ^{131}I exposure counties near Hanford and for persons living in the non-exposed or minimally exposed comparison counties. During the 51 years of observation, the patterns of thyroid cancer rates were similar and provide no evidence that radioactive ^{131}I releases have increased the occurrence of thyroid cancer in the exposure counties compared with comparison counties matched on proximity and socio-economic and demographic characteristics.

Studies of radiation-induced thyroid cancer

Because ^{131}I was the primary radionuclide released from Hanford, a discussion of radiation-induced thyroid cancer is presented. It should be noted that ^{131}I (and not a mixture of radioiodines) was released, and the low dose rate associated with the 8-d half life of ^{131}I might be expected to result in a lower risk of thyroid cancer than acute exposures to penetrating x rays or gamma rays or to the shorter-lived radioiodines (^{132}I, ^{133}I, and ^{135}I) (IARC 2001; NCRP 1985).

More is known about radiation as a carcinogen, and radiation-induced thyroid cancers in particular, than virtually any other human carcinogen (Hall and Holm 1998). There are over 20 well-designed epidemiologic studies with individual estimates of radiation dose to the thyroid gland (Ron et al. 1995; Shore 1996; Hall and Holm 1998; Boice 1998, 2005, 2006b; UNSCEAR 2000; Damber et al. 2002; Dickman et al. 2003). They include studies of atomic bomb survivors, persons exposed to radioactive fallout, radiologists and nuclear workers; newborn infants exposed to radiotherapy for enlarged thymus glands or hemangiomas; children treated for ringworm of the scalp, enlarged tonsils, and cancer; young adults given radiotherapy for Hodgkin's disease; women treated for cervical cancer; patients given bone marrow transplants; and patients administered radioactive ^{131}I to diagnosis or treat thyroid disease.

A notable feature of studies of radiation-induced thyroid cancer is the effect of age at exposure on future risk (Hempelmann 1968). The younger a person is at the time of exposure, the higher the future risk of developing thyroid cancer. Except at high therapeutic doses, exposures over the age of 20 y have not been found to significantly increase the risk of thyroid cancer. The best estimate of risk following acute exposure in childhood to x rays or gamma rays comes from a pooled analysis of several cohort studies by Ron et al. (1995): the excess relative risk (ERR) per Gy = 7.7, i.e., the RR at 1 Gy or 100 rad is estimated to be 8.7 following exposures in childhood. The risks of thyroid cancer following exposure to ^{131}I are less understood (NCRP 1985; UNSCEAR 2000; IARC 2001).

Studies of populations living in areas of high natural background radiation do not indicate an increase in thyroid neoplasms or changes in serum levels of thyroid hormones with lifetime exposure to gamma rays of the order of 0.14 Gy (Wang et al. 1990; Upton 1990). Clinical examinations of a thousand women living in high natural background areas compared to a thousand women living in low background areas indicated a difference in chromosomal abnormalities in circulating lymphocytes, but no difference in thyroid nodules or elevated levels of thyroid antibodies. The background radiation exposed the thyroid gland at a very low rate. ^{131}I, because of its 8-d half life, also releases its energy in the thyroid gland slowly and over a period of about a month or two after a single intake. The releases of ^{131}I from Hanford occurred over a period of years such that the overall rate of exposure was very low.

The Chernobyl power plant accident in 1986 exposed large numbers of the populations of Ukraine, Belarus, and the Russian Federation to radioactive fallout (UNSCEAR 2000). Of particular concern is the exposure to radioactive iodines. Large excesses of thyroid cancer have been reported (Jacob et al. 1999; UNSCEAR 2000), but only a few analytic studies have been reported to date (Astakhova et al. 1998; Davis et al. 2004b; Cardis et al. 2005). Additional analytic studies are anticipated in the near future (Stezhko et al. 2004; Likhtarov et al. 2005). There are major difficulties in interpreting these studies due to the introduction of extensive screening activity shortly after the Chernobyl accident, the use of potassium iodine after the accident, the influence of shorter-lived radioiodines, and the affect of diets deficient in stable iodine (UNSCEAR 2000; IARC 2001; Moysich et al. 2002).

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A substantial portion of the thyroid dose to some (Jacob et al. 1999; Balonov et al. 2003), but not all (Gavrilin et al. 2004) populations living near the Chernobyl reactor site was from short-lived radioiodines, similar in some respects to the Marshallese Islanders exposed to heavy nuclear fallout in 1954 (Conard 1984). Even the study in Gomel with apparently low mean exposure to shorter-lived radionuclides (Gavrilin et al. 2004) had found that the association between thyroid cancer and radiation was only in those areas near Chernobyl where the exposure to short-lived radioiodines was highest (Astakhova et al. 1998). The low dose rate associated with ^{131}I decay (i.e., it will take several months for ^{131}I to decay completely after ingestion or inhalation) and the inhomogeneous distribution of dose in the thyroid gland would be expected to carry a lower risk of thyroid disease than that from the shorter-lived radioiodines (^{132}I, ^{133}I, and ^{135}I), which deposit their energy at a higher rate (half lives from 2 to 20 hours) and more uniformly irradiate the thyroid gland, similar to external x rays (Saenger et al. 1963; Conard 1984; NCRP 1985; IARC 2000; Gilbert et al. 2002).

Another uncertainty in the Chernobyl studies of thyroid cancer is the influence of diets deficient in iodine (UNSCEAR 2000; Shakhtarin et al. 2003). "Iodine as a constituent of thyroxine, the hormone of the thyroid gland, is often deficient in inland areas, where geological factors and the absence of seafood produce a diet low in iodine. The potential increase of thyroid dose per unit uptake in humans with iodine-deficient diets is a major concern in radiation protection. It is still not known whether the higher stimulation of the gland in iodine deficiency by endogenous hormones will also alter the radiosensitivity of the stem cells and the risk coefficient for thyroid carcinoma . . . Initial measurements of iodine in urine from Belarus indicated that areas most heavily affected by iodine deposition are also deficient in a dietary supply of iodine and are endemic goiter areas" (UNSCEAR 2000). Recently, a study of 276 children with confirmed thyroid cancer in Belarus and Russia evaluated iodine deficiency as a cofactor modifying the effect of radiation from Chernobyl (Cardis et al. 2005). Not only was the radiation risk 3 times higher in the iodine-deficient areas, but there was no significant risk seen among children residing in areas of higher iodine soil content who subsequently took potassium iodide supplements. These results would caution against generalizing the Chernobyl findings to other exposed populations of children whose diets are not deficient in iodine (Boice 2005).

The authors of an earlier analytic study (Astakhova et al. 1998) were also concerned that the use of potassium iodine (KI) to block the uptake of radioiodines after the accident may have accounted for some of the inconsistencies in their findings, and these concerns were confirmed by the authors of a recent study (Cardis et al. 2005). Cardis et al. (2005) concluded that dietary supplements containing KI substantially reduced the risk of radiation-induced thyroid cancer, even if taken many months or years after the exposure occurred when blockage of ^{131}I was no longer possible since ^{131}I had already decayed. The explanation for this reduction in risk following long-term KI administration is unclear. Conceivably, the continued administration of KI in areas of endemic goiter might restore normal levels of iodine to the diet and reduce stimulation of the thyroid gland by thyroid stimulating hormone (TSH). Reducing the promoting activity of TSH might retard the development of any precancerous lesions associated with prior radioiodine exposure. Animal studies provide some support for this possibility in that the frequency of thyroid tumors is reduced following radioactive iodine administration if thyroid stimulation is decreased (Lindsay et al. 1966; Williams et al. 1993).

Excess thyroid cancers have occurred in populations exposed to a mixture of radioiodines, including ^{131}I and the shorter-lived isotopes (^{132}I, ^{133}I, and ^{135}I), but to date it has not been possible to identify a component of risk due to ^{131}I alone (UNSCEAR 2000; IARC 2000, 2001). Studies of patients administered ^{131}I for diagnostic purposes, however, have not shown an increase in thyroid cancer, after excluding persons given ^{131}I because of a suspicion of a thyroid tumor. Studies that focused on ^{131}I exposures in childhood also have failed to find an increase. Studies of patients administered ^{131}I for therapeutic purposes are inconsistent, and the small number of reported excess thyroid cancers appear related to an association with the underlying thyroid disease being treated or appear to have been already present.

A study of over 24,000 Swedish patients examined for reasons other than a suspicion of a thyroid tumor failed to link the incidence of any cancer with diagnostic doses of ^{131}I (Holm et al. 1988, 1989; Hall et al. 1996; Dickman et al. 2003). The study provided essentially complete follow up for cancer incidence using the exceptionally high quality national cancer registration system in Sweden. The average follow up was 27 y (maximum 47 y). The amount of ^{131}I administered was accurately known for all subjects, and the estimated dose to the thyroid on average was 0.94 Gy (94 rad). A substantial excess of thyroid cancer was anticipated, but no increase was seen: 36 thyroid cancers were observed and 39.5 were expected (RR 0.91; 95% CI 0.64–1.26). The absence of an effect was attributed by the authors in part to a lower carcinogenic effect from internal ^{131}I exposure compared to external x rays or gamma rays,

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perhaps related to the protracted nature of the exposure (half life = 8 d) or to the distribution of dose within the gland from ^{131}I. However, because age at exposure significantly modifies the effectiveness of radiation to cause thyroid cancer (Thompson et al. 1994; Ron et al. 1995), the investigators conducted an evaluation of the children and adolescents. This evaluation of 2,367 Swedish subjects under age 20 y when administered ^{131}I also failed to reveal an increase in thyroid cancer: 3 thyroid cancers occurred and 3 were expected (RR 1.01; 95% CI 0.2–2.9) (Dickman et al. 2003).

These Swedish data on childhood exposures are also consistent with two other series of children administered radioactive ^{131}I for diagnostic purposes (Hamilton et al. 1989; Hahn et al. 2001). A study in Germany evaluated 789 children exposed under the age of 18 to ^{131}I for diagnostic reasons and 1,118 subjects not exposed to ^{131}I as children and did not detect an increased risk of thyroid cancer based on clinical examination some 20 and more years after exposure (Hahn et al. 2001). The median radiation dose to the thyroid for the exposed subjects was 1 Gy (100 rad), and the median age at first exposure was 14.9 y. Two thyroid cancers occurred among the exposed subjects and three among the non-exposed, resulting in an RR of 0.86 (95% CI 0.14–5.13). In a U.S. study based on questionnaire responses, Hamilton et al. (1989) studied the incidence of thyroid cancer in 3,503 children who underwent thyroid examinations with ^{131}I between 1947 and 1967 in 21 clinical centers (Chiacchierini 1990). The mean thyroid dose was approximately 0.8–1.0 Gy (80–100 rad), the mean follow-up was 27 y, and the median age at ^{131}I administration was 11 y. There were 2,910 study subjects 10 y of age or younger at the time of ^{131}I administration, and 1,107 were 5 y of age or younger. Four thyroid cancers were observed 5 y or more after exposure and 3.7 were expected based on expectation in the general population (RR 1.08; 95% CI 0.3–2.8). One thyroid cancer reported two years after ^{131}I administration of unknown quantity was excluded. The small number of cancers occurring in the non-exposed groups, only one, precluded their use as a meaningful comparison.

The three studies of children administered relatively high doses of ^{131}I for diagnostic purposes (Table 6), taken together (RR 1.0 at 1 Gy; 95% CI 0.4, 2.0), are not consistent with the predicted RR of 8.7 at 1 Gy (100 rad) that would have been expected based on studies of childhood exposure to acute x rays or gamma rays of comparable doses of about 1 Gy (Ron et al. 1995). The predicted RR from acute exposures for children aged 10–19 y would have been about 4.0 at 1 Gy (100 rad) (Thompson et al. 1994), which is still inconsistent with the combined data (Table 6). These studies provide additional evidence that the risk of thyroid cancer following ^{131}I exposure in childhood is likely much lower than seen following acute exposures to x rays or gamma rays.

A fourth study of children exposed to ^{131}I alone without contamination with other shorter-lived radioactive iodines involved clinical and laboratory studies of persons potentially exposed to ^{131}I from the Hanford site while living in Washington State (Davis et al. 2002, 2004a; Kopecky et al. 2004). The exposure to ^{131}I occurred between 1944 and 1957 and was due to releases from the Hanford site (Napier 2002). Births occurring in 1940–1946 within the four counties (Franklin, Adams, Benton, Walla Walla—the same counties we studied) in Washington with the highest estimated exposure to ^{131}I (Napier 2002) and births within three minimally exposed counties (Okanogan, Stevens, Ferry) were selected for study. About 5,200 births were identified and 3,440 subjects participated in a clinical examination and laboratory blood study during the years 1992–1997, or some 40 or more years after exposure. A comprehensive dosimetry program estimated the thyroid doses (0.17 Gy mean; maximum >1 Gy). Consistent with the three diagnostic ^{131}I studies of children above, thyroid cancer (n = 19) was not significantly increased based on a dose-response analysis (Davis et al. 2002, 2004a). Neither was there evidence for a statistically significant increase in any of 17 measures of thyroid disease, including all thyroid neoplasms (n = 33), thyroid benign nodules (n = 249), hypothyroidism (n = 267), autoimmune thyroiditis (n = 625), or any ultrasound-detected thyroid abnormality (n = 1,546). Monte Carlo simulations indicated that the Hanford Thyroid Disease Study (HTDS) had substantial statistical power, even to detect

Table 6. Studies of children administered diagnostic doses of ^{131}I.

Study	No. exposed to ^{131}I	Observed cases	Expected cases	Mean dose (Gy)	Excess RR per Gy (95% CI)
Sweden (Dickman et al. 2003)	2,367	3	2.97	0.94	0.01 (−0.8, 1.9)
Germany (Hahn et al. 2001)	789	2	2.32	1.00	−0.14 (−0.9, 4.1)
U.S. (Hamilton et al. 1989)	3,503	4[a]	3.7	0.83[b]	0.08 (−0.7, 1.8)
Combined	6,659	9	8.99	0.89	0.00 (−0.6, 1.0)

[a] One thyroid cancer reported 2 y after ^{131}I administration of unknown quantity was excluded. If this case were included in the combined analysis the ERR per Gy would be 0.11 (95% confidence interval −0.5, 1.6).
[b] Approximate mean dose computed from Table 19 of Hamilton et al. (1989).

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relative risks of the order of 1.05 to 2.14 at thyroid mean dose levels of 0.17 Gy (Kopecky et al. 2004).

While it is virtually impossible to prove the negative, that is, that ^{131}I is not a cause of thyroid disease, the HTDS study provides little evidence that living near the Hanford site during the years of ^{131}I exposure affected the occurrence of thyroid disease in the most susceptible group, i.e., persons who as newborns or as children were potentially exposed to ^{131}I. The excess RR at 1 Gy for the HTDS was estimated by the authors to be a nonsignificant 0.7 (Davis et al. 2004a). At face value, this would suggest that the biological effectiveness of ^{131}I to cause thyroid cancer is a factor of 11 lower than x rays or gamma rays for which the excess RR at 1 Gy is estimated to be 7.7 for childhood exposures (Ron et al. 1995). Our thyroid cancer mortality results over the years 1950–2000 are consistent with the conclusions of the HTDS study that exposures to ^{131}I did not affect the occurrence of thyroid disease later in life (Davis et al. 2004b).

Strengths and limitations

Our county mortality study covered a long time frame, over 50 y, which enabled detailed analyses of several specific cancers. Comparisons of cancer rates just after, during, and many years after the releases of ^{131}I from the Hanford site could be made. Further comparisons with demographically similar counties in the state of Washington and with the entire United States were possible. The numbers of total cancer deaths between 1950–2000, over 14,000 and 28,000 in exposed and comparison counties, respectively, was such that any differences could be identified, if they were present. The methodology used was the same as that employed by the National Cancer Institute in a similar, but larger-scale investigation of mortality in counties throughout the United States with nuclear facilities, including electrical utilities, uranium processing plants, and weapons production laboratories (Jablon et al. 1990, 1991). Similar to our findings, the National Cancer Institute concluded that increased cancer risks were not associated with living in counties with nuclear facilities and associated radiation activities.

The cancer data reported herein resulted from routinely collected mortality statistics, and were not from an experimental study where individuals would be randomly assigned exposures and followed forward in time. Information on radiation exposures was not known for individuals countywide, although estimates for many individuals in exposed counties indicate that the mean thyroid dose was of the order of 0.17 Gy (17 rad) (Davis et al. 2002, 2004a). Although counties were matched using available data concerning racial composition, urban-rural mix, income, and other factors, it is not possible to choose comparison counties that are exactly the same as the study counties. Counties, for example, can vary with respect to industries, occupations, and lifestyle. The difference in lung cancer rates, for example, might indicate a difference in smoking habits between study and comparison counties. Cancer deaths in each county were also compared with the numbers expected on the basis of concurrent U.S. mortality rates. The absence of any unusual or significant trends in cancer rates over time within the study counties indirectly addresses the possibility of differences arising solely from inadequate comparison populations.

This study relied on mortality data. Although the accuracy of the cause of death information on death certificates is variable, this inaccuracy is less for cancer than other causes even during the early years of this study (Percy et al. 1981). Further, the quality of death certificate information would be expected to be similar for the study counties and the neighboring comparison counties. Mortality nearly equals incidence for many cancers that have high fatality rates, such as cancers of the lung, stomach, bone, connective tissue, liver, and adult leukemia. Mortality data, however, are not optimal for monitoring such cancers as those of the thyroid or childhood leukemia, for which improved therapy has markedly lowered death rates in recent years while not affecting incidence. The numbers of deaths due to thyroid cancer (n = 33 and 76) and childhood leukemia (n = 71 and 103) in the study and comparison counties, respectively, however, were large enough overall to be informative. Because mortality and incidence rates are highly correlated, the good survival associated with thyroid cancer and childhood cancer will reduce statistical power for evaluating effects, but is not necessarily a methodological deficiency if numbers of deaths are sufficiently large. The upper 95% confidence limits indicate that relative risks higher than 1.26 and 1.43 for thyroid cancer and childhood leukemia, respectively, could be excluded with high confidence.

The risk of radiation-induced thyroid cancer, however, is also related to the age at which exposure occurs, and the current study includes many adults for whom the risk would be expected to be much lower than for children. A birth cohort analysis was conducted focusing on childhood exposures, and no increase in thyroid cancer was found. Persons with the potential for childhood exposure to ^{131}I would have been born between 1925 and 1957 and thus under the age of 20 y sometime during the period 1944–1957 when ^{131}I was released. For these persons with the potential for childhood exposure to ^{131}I, there was no indication of an increased risk of thyroid cancer based on 14 subsequent deaths (RR 0.99; 95% CI 0.51–1.90). These mortality data on thyroid

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cancer are consistent with the comprehensive study of thyroid cancer prevalence and other thyroid conditions recently reported among children living near Hanford during the time of ^{131}I releases (Davis et al. 2002, 2004a).

Mortality rates have changed over time for a number of reasons including improvements in treatment and changes in lifestyle. Mortality rates for childhood leukemia have decreased in the entire United States during the study time period, whereas mortality rates for lung cancer have increased up until about 1990 when a downturn began (Jemal et al. 2005). Our study compares mortality rates in the exposed counties with those in nearby comparison counties by calendar periods to account for such changes over time to the extent possible.

Because some individuals in study counties lived at some distance from the Hanford site, local effects would be difficult to detect using county death rates if there were any appreciable dilution of exposure by distance. However, the ^{131}I releases from the Hanford site have been extensively evaluated, and wind patterns, which were taken into account in the selection of the study counties, indicate the potential for most county residents to be exposed. Further, the main contribution to thyroid dose was not from inhalation but from the consumption of milk containing ^{131}I which was not restricted to proximity to the Hanford site (Farris et al. 1996).

This was an "ecological" survey in which the exposures, if any, of individuals are not known. Persons who lived in particular counties at the time of death may not have been long-term residents. Some residents will have moved elsewhere and died in another part of the country. Although there have been population changes within the study and comparison counties over the years, growth has been comparable as suggested by the decennial census data.

Despite the limitations inherent in a geographic correlation study of cancer mortality in the counties exposed to ^{131}I from the Hanford releases, similar methods used have been applied effectively in the past to identify environmental carcinogens when exposures were high and long-term. For example, based on findings from the "cancer maps" constructed from county mortality statistics by the National Cancer Institute (Devesa et al. 1999a and b), counties with shipyard industries were found to have elevated lung cancer death rates, particularly among men. Subsequent case-control studies in the high-risk areas linked the excess lung cancer deaths to occupational exposures to asbestos (Blot et al. 1978). It might be noted that the NCI cancer maps, similar to our community study, do not indicate that cancer mortality in the exposed counties is higher than the rest of the U.S. or that changes in cancer rates over time differ from those of the rest of the U.S. (Devesa et al. 1999a). Further, the initial studies around Chernobyl linking radioiodine exposure to thyroid cancer were all ecological (Jacob et al. 1999) and it is only recently that analytical studies with individual dose estimates have confirmed the earlier conclusions (Astakhova et al. 1998; Davis et al. 2004b; Cardis et al. 2005).

CONCLUSION

This study, then, provides no evidence that persons living near the Hanford site were at increased risk of cancer, and thyroid cancer in particular, because of their residential history and potential exposure to ^{131}I or other radioactive elements released from the Hanford facility during the years of operation. These data are also consistent with an earlier study conducted by the National Cancer Institute that did not show increased cancer rates among persons residing near the Hanford reservation (Jablon et al. 1990). Although limited by the ecologic design, the findings with regard to thyroid cancer are also consistent with the Hanford Thyroid Disease Study that did not find an association between thyroid cancer and estimated radiation doses to the thyroid gland of infants and children exposed to ^{131}I (Davis et al. 2004a).

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REFERENCES

Astakhova LN, Anspaugh LR, Beebe GW, Bouville A, Drozdovitch VV, Garber V, Gavrilin YI, Khrouch VT, Kuvshinnikov AV, Kuzmenkov YN, Minenko VP, Moschik KV, Nalivko AS, Robbins J, Shemiakina EV, Shinkarev S, Tochitskaya SI, Waclawiw MA. Chernobyl-related thyroid cancer in children of Belarus: a case-control study. Radiat Res 150:349–356; 1998.

Balonov M, Kaidanovsky G, Zvonova I, Kovtun A, Bouville A, Luckyanov N, Voilleque P. Contributions of short-lived radioiodines to thyroid doses received by evacuees from the Chernobyl area estimated using early in vivo activity measurements. Radiat Prot Dosim 105:593–599; 2003.

Blot WJ, Harrington JM, Toledo A, Hoover R, Heath CW, Jr, Fraumeni JF, Jr. Lung cancer after employment in shipyards during World War II. N Engl J Med 299:620–624; 1978.

Boice JD, Jr. Radiation and thyroid cancer: what more can be learned? Acta Oncol 37:321–324; 1998.

Boice JD, Jr. Radiation-induced thyroid cancer—what's new? J Natl Cancer Inst 97:703–705; 2005.

Boice JD, Jr. Radiation epidemiology. In: Schottenfeld D, Fraumeni JF, Jr, eds. Cancer epidemiology and prevention, 3rd edition. New York: Oxford University Press; 2006a: 259–293.

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

Boice JD, Jr. Thyroid disease 60 years after Hiroshima and 20 years after Chernobyl (editorial). JAMA 295:1060–1062; 2006b.

Boice JD, Jr, Bigbee WL, Mumma MT, Blot WJ. Cancer mortality in counties near two former nuclear materials processing facilities in Pennsylvania, 1950–1995. Health Phys 85:691–700; 2003a.

Boice JD, Jr, Mumma M, Schweitzer S, Blot WJ. Cancer mortality in a Texas county with prior uranium mining and milling activities, 1950–2001. J Radiol Prot 23:247–262; 2003b.

Breslow N, Day N. Statistical methods in cancer research. Vol 2. Lyon, France: International Agency for Research on Cancer; IARC Scientific Publication 82; 1987.

Cardis E, Kesminiene A, Ivanov V, Malakhova I, Shibata Y, Khrouch V, Drozdovitch V, Maceika E, Zvonova I, Vlassov O, Bouville A, Goulko G, Hoshi M, Abrosimov A, Anoshko J, Astakhova L, Chekin S, Demidchik E, Galanti R, Ito M, Korobova E, Lushnikov E, Maksioutov M, Masyakin V, Nerovnia A, Parshin V, Parshkov E, Piliptsevich N, Pinchera A, Polyakov S, Shabeka N, Suonio E, Tenet V, Tsyb A, Yamashita S, Williams D. Risk of thyroid cancer after exposure to 131I in childhood. J Natl Cancer Inst 97:724–732; 2005.

Chiacchierini RP. Iodine-131 exposures and neoplasia. Radiat Res 124:359–360; 1990.

Conard RA. Late radiation effects in Marshall Islanders exposed to fallout twenty eight years ago. In: Boice JD, Jr, Fraumeni JF, Jr, eds. Radiation carcinogenesis: epidemiology and biological significance. New York: Raven Press; 1984: 57–71.

Damber L, Johansson L, Johansson R, Larsson LG. Thyroid cancer after x-ray treatment of benign disorders of the cervical spine in adults. Acta Oncol 41:25–28; 2002.

Davis S, Kopecky KJ, Hamilton TE, Onstad L, King BL, Saporito MS. Hanford Thyroid Disease Study. Final Report. Seattle, WA: Fred Hutchinson Cancer Research Center; CDC Conract No. 200 89 0716; 2002. Available at: http://www.cdc.gov/nceh/radiation/hanford/htdsweb/pdf/htdsreport.pdf. Accessed 8 February 2006.

Davis S, Kopecky KJ, Hamilton TE, Onstad L. Hanford Thyroid Disease Study Team. Thyroid neoplasia, autoimmune thyroiditis, and hypothyroidism in persons exposed to iodine 131 from the Hanford nuclear site. JAMA 292:2600–2613; 2004a.

Davis S, Stepanenko V, Rivkind N, Kopecky KJ, Voilleque P, Shakhtarin V, Parshkov E, Kulikov S, Lushnikov E, Abrosimov A, Troshin V, Romanova G, Doroschenko V, Proshin A, Tsyb A. Risk of thyroid cancer in the Bryansk Oblast of the Russian Federation after the Chernobyl Power Station accident. Radiat Res 162:241–248; 2004b.

Devesa SS, Grauman D, Blot WJ, Pennello GA, Hoover RN, Fraumeni JF, Jr. Atlas of cancer mortality in the United States: 1970–1994. Washington, DC: DHHS, PHS, NIH; NIH Pub. No. 99-4564; 1999a.

Devesa SS, Grauman DJ, Blot WJ, Fraumeni JF, Jr. Cancer surveillance series: changing geographic patterns of lung cancer mortality in the United States, 1950 through 1994. J Natl Cancer Inst 91:1040–1050; 1999b.

Dickman PW, Holm LE, Lundell G, Boice JD Jr, Hall P. Thyroid cancer risk after thyroid examination with 131I: a population-based cohort study in Sweden. Int J Cancer 106:580–587; 2003.

Farris WT, Napier BA, Ikenberry TA, Simpson JC, Shipler DB. Atmospheric Pathway Dosimetry Report, 1944–1992. Hanford Environmental Dose Reconstruciton Project, PNWD-2228 HEDR. Richland, WA: Battelle Pacific Northwest Laboratories; 1994.

Farris WT, Napier BA, Ikenberry TA, Shipler DB. Radiation doses from Hanford site releases to the atmosphere and the Columbia River. Health Phys 71:588–601; 1996.

Gavrilin Y, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakina E, Ulanovsky A, Bouville A, Anspaugh L, Voilleque P, Luckyanov N. Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus—Part I: 131I, short-lived radioiodines (132I, 133I, 135I), and short-lived radiotelluriums (131mTe and 132Te). Health Phys 86:565–585; 2004.

Gilbert ES, Land CE, Simon SL. Health effects from fallout. Health Phys 82:726–735; 2002.

Hahn K, Schnell-Inderst P, Grosche B, Holm LE. Thyroid cancer after diagnostic administration of iodine-131 in childhood. Radiat Res 156:61–70; 2001.

Hall P, Holm LE. Radiation-associated thyroid cancer—facts and fiction. Acta Oncol 37:325–330; 1998.

Hall P, Mattsson A, Boice JD Jr. Thyroid cancer after diagnostic administration of iodine-131. Radiat Res 145:86–92; 1996.

Hamilton PM, Chiacchierini RP, Kaczmarek RG. A follow-up study of persons who had iodine-131 and other diagnostic procedures during childhood and adolescence. Rockville, MD: U.S. Food and Drug Administration; HHS Publication FDA 89-8276; 1989.

Hempelmann LH. Risk of thyroid neoplasms after irradiation in childhood. Studies of populations exposed to radiation in childhood show a dose response over a wide dose range. Science 160:159–163; 1968.

Holm LE, Wiklund KE, Lundell GE, Bergman NA, Bjelkengren G, Cederquist ES, Ericsson UB, Larsson LG, Lidberg ME, Lindberg RS. Thyroid cancer after diagnostic doses of iodine-131: a retrospective cohort study. J Natl Cancer Inst 80:1132–1138; 1988.

Holm LE, Wiklund KE, Lundell GE, Bergman NA, Bjelkengren G, Ericsson UB, Cederquist ES, Lidberg ME, Lindberg RS, Wicklund HV. Cancer risk in population examined with diagnostic doses of 131I. J Natl Cancer Inst 81:302–306; 1989.

International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risks to humans. Ionizing radiation, part 1: x- and gamma radiation, and neutrons. Lyon, France: International Agency for Research on Cancer 75; 2000.

International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risks to humans. Ionizing radiation, part 2: some internally deposited radionuclides. Lyon, France: International Agency for Research on Cancer 78; 2001.

Jablon S, Hrubec Z, Boice JD Jr, Stone BJ. Cancer in populations living near nuclear facilities. Washington, DC: U.S. Government Printing Office; NIH Publ 90-874; 1990.

Jablon S, Hrubec Z, Boice JD, Jr. Cancer in populations living near nuclear facilities. A survey of mortality nationwide and incidence in two states. JAMA 265:1403–1408; 1991.

Jacob P, Kenigsberg Y, Zvonova I, Goulko G, Buglova E, Heidenreich WF, Golovneva A, Bratilova AA, Drozdovitch V, Kruk J, Pochtennaja GT, Balonov M, Demidchik EP, Paretzke HG. Childhood exposure due to the Chernobyl accident and thyroid cancer risk in contaminated areas of Belarus and Russia. Br J Cancer 80:1461–1469; 1999.

Jemal A, Murray T, Ward E, Samuels A, Tiwari RC, Ghafoor A, Ward E, Feuer EJ, Thun MJ. Cancer statistics, 2005. CA Cancer J Clin 55:10–30; 2005.

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Kopecky KJ, Davis S, Hamilton TE, Saporito MS, Onstad LE. Estimation of thyroid radiation doses for the Hanford thyroid disease study: results and implications for statistical power of the epidemiological analyses. Health Phys 87:15–32; 2004.

Likhtarov I, Kovgan L, Vavilov S, Chepurny M, Bouville A, Luckyanov N, Jacob P, Voilleque P, Voigt G. Post-Chornobyl thyroid cancers in Ukraine. Report 1: Estimation of thyroid doses. Radiat Res 163:125–136; 2005.

Lindsay S, Nichols CW Jr, Chaikoff IL. Induction of benign and malignant thyroid neoplasms in the rat. Induction of thyroid neoplasms by injection of 131-I with or without the feeding of diets containing propylthiouracil and/or desiccated thyroid. Arch Pathol 81:308–316; 1966.

Mantel N, Ederer F. Exact limits for the ratio of two SMR values. J Epidemiol Community Health 39:367–368; 1985.

Marsh GM, Youk AO, Stone RA, Sefcik S, Alcorn C. OCMAP-PLUS: a program for the comprehensive analysis of occupational cohort data. J Occup Environ Med 40:351–362; 1998.

Moysich KB, Menezes RJ, Michalek AM. Chernobyl-related ionising radiation exposure and cancer risk: an epidemiological review. Lancet Oncol 3:269–279; 2002.

Napier BA. A re-evaluation of the 131I atmospheric releases from the Hanford site. Health Phys 83:204–226; 2002.

National Cancer Institute. 1999 RateCalc Mortality Rate Generator, Version 3.6 user's guide. Bethesda, MD: Division of Cancer Epidemiology and Genetics; 2003.

National Council on Radiation Protection and Measurements. Induction of thyroid cancer by ionizing radiation. Bethesda, MD: NCRP; Report No. 80; 1985.

National Research Council. Review of the Hanford Thyroid Disease Study. Draft Final Report. Washington, DC: National Academy Press; 2000.

Percy C, Stanek E, III, Gloeckler L. Accuracy of cancer death certificates and its effect on cancer mortality statistics. Am J Public Health 71:242–250; 1981.

Preston DL, Shimizu Y, Pierce DA, Suyama A, Mabuchi K. Studies of mortality of atomic bomb survivors. Report 13: Solid cancer and noncancer disease mortality: 1950–1997. Radiat Res 160:381–407; 2003.

Ron E, Lubin JH, Shore RE, Mabuchi K, Modan B, Pottern LM, Schneider AB, Tucker MA, Boice JD, Jr. Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. Radiat Res 141:259–277; 1995.

Saenger EL, Seltzer RA, Sterling TD, Kereiakes JG. Carcinogenic effects of I-131 compared with x irradiation—a review. Health Phys 65:1371–1384; 1963.

Shakhtarin VV, Tsyb AF, Stepanenko VF, Orlov MY, Kopecky KJ, Davis S. Iodine deficiency, radiation dose, and the risk of thyroid cancer among children and adolescents in the Bryansk region of Russia following the Chernobyl power station accident. Int J Epidemiol 32:584–591; 2003.

Shore RE. Human thyroid cancer induction by ionizing radiation: summary of studies based on external irradiation and radioactive iodines. In: Karagoglou A, Desmet G, Kelly GN, Menzel HG, eds. The radiological consequences of the Chernobyl accident. Luxembourg: Office for Official Publications of the European Communities; 1996: 669–675.

Steenland K, Henley J, Calle E, Thun M. Individual- and area-level socioeconomic status variables as predictors of mortality in a cohort of 179,383 persons. Am J Epidemiol 159:1047–1056; 2004.

Stezhko VA, Buglova EE, Danilova LI, Drozd VM, Krysenko NA, Lesnikova NR, Minenko VF, Ostapenko VA, Petrenko SV, Polyanskaya ON, Rzheutski VA, Tronko MD, Bobylyova OO, Bogdanova TI, Ephstein OV, Kairo IA, Kostin OV, Likhtarev IA, Markov VV, Oliynik VA, Shpak VM, Tereshchenko VP, Zamotayeva GA, Beebe GW, Bouville AC, Brill AB, Burch JD, Fink DJ, Greenebaum E, Howe GR, Luckyanov NK, Masnyk IJ, McConnell RJ, Robbins J, Thomas TL, Voilleque PG, Zablotska LB. A cohort study of thyroid cancer and other thyroid diseases after the Chornobyl accident: objectives, design and methods. Radiat Res 161:481–492; 2004.

Thompson DE, Mabuchi K, Ron E, Soda M, Tokunaga M, Ochikubo S, Sugimoto S, Ikeda T, Terasaki M, Izumi S. Cancer incidence in atomic bomb survivors. Part II: Solid tumors, 1958–1987. Radiat Res 137:S17–S67; 1994.

United Nations Scientific Committee on the Effects of Atomic Radiation. 1994 Report to the General Assembly, with Scientific Annexes. Sources and Effects of Ionizing Radiation. New York: United Nations; 1994.

United Nations Scientific Committee on the Effects of Atomic Radiation. 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations; 2000.

Upton AC. Carcinogenic effects of low-level ionizing radiation. J Natl Cancer Inst 82:448–449; 1990.

U.S. Department of Commerce. 1990 census of the population. Characteristic of the population PC 90-1-B40. Washington, DC: Bureau of the Census; 1992.

Wang ZY, Boice JD, Jr, Wei LX, Beebe GW, Zha YR, Kaplan MM, Tao ZF, Maxon HR, III, Zhang SZ, Schneider AB, Tan B, Wesseler TA, Chen D, Ershow AG, Kleinerman RA, Littlefield LG, Preston D. Thyroid nodularity and chromosome aberrations among women in areas of high background radiation in China. J Natl Cancer Inst 82:478–485; 1990.

Williams D, Pinchera A, Karaoglou A, Chadwick KH, eds. Thyroid cancer in children living near Chernobyl. Report EUR 15248. Luxembourg: Commission of the European Communities; 1993: 80–81.

World Health Organization. International classification of diseases. The international statistical classification of diseases, injuries, and causes of death. Ninth revision. Geneva: World Health Organization; 1977.

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