

ORIGINAL ARTICLE

Long-term Local Cancer Reductions Following Nuclear Plant Shutdown

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ABSTRACT

Patterns of long-term health risk reduction after levels of environmental hazards decline have been documented, but are still not precisely understood. Nuclear plant shutdowns that eliminate radioactive emissions and reduce toxins in the environment and food chain have been previously linked with significant short-term declines in local infant deaths and child cancer cases. The Rancho Seco nuclear power plant in Sacramento County, California, USA ceased operating in June 1989; no other operating reactor exists within 200 miles of the site. We examine official California Cancer Registry data on cancer incidence for Sacramento County vs. the entire state, using the last two years of reactor operation (1988-1989) as a baseline; the Registry began in 1988. Temporal trends are given for Standard Incidence Ratios of all cancers combined, and by gender, race/ethnicity, common types of cancer, and child cancer. Since the late 1980s, cancer incidence in Sacramento County has declined for 28 of 31 categories (genders, races, types of cancer); 14 of these declines are statistically significant and two others borderline significant. The estimated reduction in cancer cases in the county over a 20-year period is 4,319. Many factors can result in lower cancer incidence over two decades, but elimination of radioactive isotopes should be addressed in future reports as one of these potential factors. *Biomed. Int.* 2013; 4: 12-25. ©2013 Biomedicine International, Inc.

Key words: Cancer, environmental, health, nuclear, Rancho Seco, reactors

INTRODUCTION

A number of nuclear power reactors, first operated in the 1950s, have been permanently shut down. In the U.S., 23 of the 127 reactors have been closed. Twelve (12) of these 23 were closed permanently from 1987-1998, several of which were relatively large units.¹ The last reactor closing occurred in January 1998, meaning that the post-closure periods are lengthy. Reactor shutdown means the immediate end of all radioactive emissions into the environment, plus the rapid elimination of short-lived (and gradual reduction in long-lived) radioisotopes in the environment. While the extent of long-term changes in local radioactive contamination and health near closed reactors merits consideration, it remains virtually unexamined.

Methods of assessing risk reduction after the elimination of a health hazard continue to evolve and present varying results. The highest percentage of U.S. adults over 18 years of age who smoked (42.4% in 1965) was followed by decades of decline to 20.6% by 2009.² But U.S. age-adjusted lung cancer incidence for all ages continued to rise until 1992; the decline from 1992 to 2009 was just 15.4%, from 69.45 to 58.75 cases per 100,000 persons.³

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Several reasons could account for this dichotomy, including latency between smoking and manifestation of disease, along with factors other than tobacco use that affect lung cancer risk. No cancers are randomly distributed in any population, and our proposed method will help to elucidate the effects of one potential risk factor.⁴⁻⁶

The short-term health effects of reduced fission products have been examined. The 1963 Partial Test Ban Treaty, which ended all above-ground atom bomb detonations by the United States, Soviet Union, and United Kingdom, resulted in the elimination of all short-lived isotopes from tests within months. Long-lived isotopes in the environment dropped rapidly as well; Strontium-90 in raw milk in nine U.S. cities during the spring of 1964⁷ dropped from 30 to 6 picocuries per liter just six years later.⁸

The U.S. infant mortality rate, which had only fallen from 28.4 to 24.7 deaths per 1000 live births (0.93% per year) between 1951 and 1965, the period when nuclear weapons were tested in the atmosphere and fallout was rising, steadily declined to 19.1 (3.77% per year) by 1971, after the test ban treaty went into effect.⁹ A similar pattern occurred in the United Kingdom, a pattern one researcher attributed to atmospheric nuclear testing and the subsequent ban.¹⁰ In Connecticut, the only state with a reliable cancer incidence registry at that time, cancer incidence diagnosed in children under five years dropped 30% (20.38 to 14.21 cases per 100,000) between 1962-1964 and 1967-1969, following a 40% rise after 1948-50, just before bomb testing began. For leukemia incidence age 0-4, the change was +121% during bomb testing, and -53% in the five years after test cessation.¹¹

Data addressing changes in health after the introduction of environmental fission products from nuclear reactors – not just from atom bomb tests – are also available. The 1990 study by the U.S. National Cancer Institute included temporal mortality data near 62 U.S. nuclear plants, only four of which had available incidence data before and after plant startup.¹² Table 1 documents consistent increases in (county vs. state) Standard Incidence Ratios near each of the four plants for childhood cancer age 0-19, and thyroid cancer for all ages. The total change in SIR for both types of cancer was 0.17 (0.903 to 1.076 for childhood, 0.785 to 0.950 for thyroid), significant at $P < 0.05$.

Examination of the short-term local health status changes in young persons immediately after shutdown of eight U.S. nuclear plants between 1987 and 1997 compared infant mortality for the two years before shutdown (including shutdown year) with the two years following. Rates in each of the eight areas decreased more rapidly than in the U.S. as a whole; the total decline for the eight areas was -17.4% vs. -6.4% nationally. The three areas for which cancer incidence was available showed a decrease of -25.0%, in children age 0-4, vs.

Table 1: Standard Incidence Ratios, County vs. State Rate (Adjusted to 1950 U.S. Standard Population; Before and After Startup of Nuclear Plants in Connecticut and Iowa; Thyroid Cancer (All Ages) and Childhood Cancer (Age 0-19)).

	Plant	County	Startup (years before)	Startup (years after)	SIR (cases) (before Start)	SIR (cases) (after start)	Change
Thyroid Cancer	Haddam Neck	Middlesex, CT	1950-67	1968-84	0.94 (36)	1.03 (76)	+9
	Millstone	New London, CT	1950-70	1971-84	0.69 (64)	0.79 (90)	+10
	Duane Arnold	Benton/Linn, IA	1969-74	1975-84	0.92 (23)	1.13 (77)	+21
	Ft. Calhoun	Harrison, IA	1969-73	1974-84	0.52 (1)	0.92 (6)	+40
	TOTAL				0.785 (124)	0.950 (249)	+17*
Childhood Cancer Age 0-19	Haddam Neck	Middlesex, CT	1950-67	1968-84	0.86 (62)	0.96 (95)	+10
	Millstone	New London, CT	1950-70	1971-84	0.88 (173)	1.03 (172)	+15
	Duane Arnold	Benton/Linn, IA	1969-74	1975-84	1.06 (50)	1.28 (119)	+22
	Ft. Calhoun	Harrison, IA	1969-73	1974-84	0.82 (2)	1.05 (9)	+23
	TOTAL				0.903 (287)	1.075 (395)	+17*

*Significant at $P < 0.05$

a rise of 0.5% for the entire U.S.¹³

A more detailed analysis of local short-term health changes after nuclear plant shutdown focused on the Rancho Seco reactor in California.¹⁴ The reactor closed permanently on June 6, 1989 so health outcomes in the periods 1988-1989 and 1990-1991 were compared. Concentrations of radioisotope intake, by breathing or through the food chain, decreased between these two periods (other types of environmental radioactivity such as leakage in the ground are generally confined to the plant and not part of the food chain). Moreover, any short-term reductions in disease or death rates are more likely to be detected in the very young. Children age 0-2 and 2-16 years have been estimated to be 10 and 3 times more sensitive to radiation exposure, respectively, than adults.¹⁵ The developing fetus undergoes rapid cell proliferation, self-programmed cell death (apoptosis), and cell rearrangement. The developing infant is similarly susceptible to cellular and metabolic damage. Unrepaired damage becomes magnified with time.¹⁶

In the two years after shutdown near Rancho Seco, declines in local odds ratios were sharper than the U.S. change for still births >20 weeks gestation, deaths age 0-1 (all causes and congenital anomalies), deaths age 1-4 (birth defects and all causes excluding accidents, homicide, and suicide), and cancer incidence age 0-4. These findings suggest that the closing of Rancho Seco reduced risk to health for local residents, and provide a basis for conducting analyses on potential long-term health changes.

Rancho Seco has been selected for study in this report for several reasons. The site is located in Sacramento County, an area with a relatively large 2010 population of 1,418,788,¹⁷ meaning that larger numbers of local cases will carry greater statistical power. The closest operating nuclear plant is Diablo Canyon, over 200 miles to the south. Rancho Seco has been closed for over 23 years, providing a long period to examine post-shutdown local health patterns. There is a large county-specific data base available in the state of California for cancer incidence, from 1988-2009. Finally, the Sacramento area uses more electricity from renewable non-polluting sources than other areas in California. The Sacramento Municipal Utility District, which supplies electricity to the county, sourced 21% of its power from renewable sources by 2010, the highest of any California utility.¹⁸ The County receives only 12% of its electricity from coal¹⁹ compared to 45% nationally.²⁰ Less pollution from other power sources would theoretically accentuate any improvements in health after reactor shutdown.

MATERIALS AND METHODS

The Rancho Seco nuclear reactor lies within 20 miles of most county residents. While proximity to a pollution source is not the only factor in evaluating health risk, examining the health of nearby residents is a commonly used technique. The 1990 National Cancer Institute study of cancer near U.S. nuclear plants compared the Standard Mortality Ratio for the most proximate county(ies) to 62 U.S. nuclear plants before and after startup.¹² Rancho Seco was one of the plants studied, and the authors selected the California counties of Sacramento, Amador, and San Joaquin as the most proximate counties (Sacramento accounts for 66% of the population of these three counties).

Cancer morbidity changes in Sacramento County post-shutdown can be compared with a "control" county in California, the state of California, or the United States. However, no single county in the state with a large, mostly urban population has similar demographic

temporal changes. The closest is Contra Costa, with a population of just over 1 million, and with similar age, race, and gender distributions but a substantially higher income and lower poverty rate.

Demographic changes throughout California are relatively close to those of Sacramento County (Table 2). The gender distributions in both Sacramento County and California have changed little in the past several decades. There have been substantial changes in racial/ethnic mix, with increases in Hispanics and non-Hispanic Asians offsetting reductions in non-Hispanic whites. In addition, the 2006-2010 poverty rate was nearly identical in the state (13.7%) and the county (13.9%).¹⁷ Thus, the state of California can be used as an acceptable control for Sacramento County in evaluating changes in cancer rates for both genders and all races combined.

Table 2: Demographic Changes, 1988-2009 (Sacramento County and California).

	County	State	County	State	County	State	County	State	County	State	County	State
	% White*		% Black*		% Asian*		% Hispanic		% Female		% Male	
1988	69.9	58.7	9.1	7.2	8.5	8.6	11.6	24.9	51.1	50.0	48.9	50.0
2009	52.9	42.7	10.8	6.4	14.9	13.2	20.5	37.0	50.8	50.1	49.2	49.0
% Change	-17.0	-16.0	+1.7	-0.8	+6.4	+4.6	+8.9	+12.2	-0.3	+0.1	+0.3	-0.1

* Excluding Hispanic

The health status data to be analyzed focused on cancer incidence. The California Cancer Registry makes incidence data for each year from 1988 to 2009 available on its web site; consistent with methods used in prior analyses,^{13,14} the pre-shutdown period will be 1988-1989 while the post-shutdown years will be 1999-2009. Incidence data are available for each county, race, gender, and type of cancer. Cancer incidence rates are cases per 100,000 persons per year, adjusted to the 2000 U.S. standard population.

The state registry has mandated reporting of all newly-diagnosed cancer cases beginning on January 1, 1988. Cancer registrars at hospitals, physician offices, and other providers submit information on each case to the county health department, which then sends data to its state government counterparts. Monitoring is conducted by state officials to ensure the accuracy and comprehensiveness of submitted data. The ICD-O system is used to assign a code denoting the type of cancer. The zip code of residence at diagnosis is used to assign cases by county. The state ensures that non-residents diagnosed in the state are not included, and maintains agreements with other states to submit data on California residents diagnosed with cancer in another state.

Cancer mortality data were not included in this report. While changes in mortality, not just incidence, can result of risk reduction, death rates are affected by factors such as quality of and access to health care and should therefore be examined in a separate analysis. Trends in county vs. state cancer rates, in annual cases per 100,000 adjusted to the 2000 U.S. standard population, were analyzed by race, gender, and type of cancer. Analysis of cancer incidence among children will be included in the report, as the developing fetus, infant, and young child are far more sensitive to radiation exposure than are adults.¹⁵ Only invasive cancers were included in this study. Benign neoplasms constitute less than 10 percent of all tumors reported in cancer registries, and were excluded from this study as they may or may not eventually become cancerous. The analysis subdivided the period after reactor shutdown into five year groups: 1990-1994, 1995-1999, 2000-2004, and 2005-2009. Trends for each gender, race, and most commonly diagnosed cancer were analyzed as well.

The significance of the change in differences in Sacramento County and California cancer incidence rates between the pre-shutdown and post-shutdown periods was generated using a previously described formula to calculate a 95% confidence interval, specifically used to estimate intervals for age-adjusted cancer rates.²¹ If the lower bound of the confidence interval is above zero, the change is significant at $P < 0.05$. The formula for calculating confidence intervals for the change in Standard Incidence Ratios between two periods is as follows: $(SIR_2 - SIR_1) \pm 1.96 * \text{SQRT}(\text{VAR SIR}_1 + \text{VAR SIR}_2)$, where

$$\text{VAR SIR}_1 = \left[\left[(\text{Co. SE}_1^2 * \text{St. Rate}_1^2) + (\text{St. SE}_1^2 * \text{Co. Rate}_1^2) \right] / \text{St. Rate}_1^4 \right]$$

$$\text{VAR SIR}_2 = \left[\left[(\text{Co. SE}_2^2 * \text{St. Rate}_2^2) + (\text{St. SE}_2^2 * \text{Co. Rate}_2^2) \right] / \text{St. Rate}_2^4 \right]$$

SIR_1 = Standard Incidence Ratio for pre-shut down period (1988-1989)

SIR_2 = Standard Incidence Ratio for post-shut down period (often 1990-2009)

$\text{Co. SE}_1(2)$ = Standard Error for county pre (post)-shut down; $(\text{High Limit } 95\% \text{ CI} - \text{Low Limit } 95\% \text{ CI})/2/1.96$

$\text{St. SE}_1(2)$ = Standard Error for state pre (post)-shut down $(\text{High Limit } 95\% \text{ CI} - \text{Low Limit } 95\% \text{ CI})/2/1.96$

$\text{Co. Rate}_1(2)$ = County Age-Adjusted Incidence Rate per 100,000, pre (post)-shut down

$\text{St. Rate}_1(2)$ = State Age-Adjusted Incidence Rate per 100,000, pre (post)-shut down

RESULTS

Release of radioisotopes into the environment from Rancho Seco began in September 1974 as the reactor achieved initial criticality. While the exact amount of emission from each isotope is not known, the total officially reported 1975-1989 release of Iodine-131 and particulates – all isotopes with a half life over eight days – amounted to 0.14 curies. This total is equivalent to about 1% of the official environmental releases of 14.2 curies of I-131 and particulates during the Three Mile Island meltdown in March 1979.²² These releases account for a small portion of the radioactive waste produced at Rancho Seco; the remainder was stored in deep pools of constantly-cooled water in the form of used fuel rods, then transferred to “dry” casks of steel and concrete.

Environmental levels of radioactivity are measured by the U.S. Environmental Protection Agency.²³ Levels of the radioisotopes Iodine-131 and Cesium-137 were measured 14 times each year during the late 1980s. Table 3 shows the change in average levels of both chemicals in pasteurized milk in Sacramento before and after Rancho Seco closed, during the periods January 1987-May 1989 and June 1989-December 1990.

Table 3: Change in Iodine-131 and Cesium-137 Concentrations (Pasteurized Milk, Sacramento California, 1987-1990).

Radionuclide	Average picocuries per liter (n)		
	1/87 to 5/89	6/89 to 12/90	% Change
Cesium-137	3.11 (36)	2.54 (20)	- 18.3%
Iodine-131	4.88 (34)	3.75 (11)	- 23.1%

Average milk concentrations of both isotopes declined after the Rancho Seco shutdown. The sharper decline in Iodine-131 is supported by the fact that this isotope is short-lived (half life 8 days) compared to Cesium-137 (half-life 30 years). These patterns can be used as a proxy for all long- and short-lived isotopes released by nuclear reactors. The contin-

ued presence of I-131 in Sacramento milk after shutdown could be explained by residual I-131 from Rancho Seco, and/or the introduction of the isotope from other areas into the local food chain. The average I-131 in picocuries per liter in early 1989, while the reactor still was operating, was 4.37 (n=6), falling to 4.23 in late 1989 (n=8), and plummeting to 2.47 in early 1990 (n=3). Thus, substantial reductions in local environmental radioactivity merit an examination of potential reductions in local cancer incidence rates after Rancho Seco shutdown.

All Types of Cancer Combined: The incidence rates for all invasive cancers combined for Sacramento County and California in the period 1988-89 and for each subsequent five year period thereafter are given in Table 4. Sacramento's rank among 47 California counties (the state has 58 counties, but some contiguous groups of less populated counties are combined) is also presented.²⁴

Table 4: Annual Incidence Rates, All Invasive Cancers Combined (Adjusted to 2000 U.S. Standard Population; Sacramento County vs. California (Standard Incidence Ratio, SIR); 1988-1989 vs. Subsequent Five-Year Periods).

Period	Cases/100,000		Cancer Cases		SIR		Rank of 47 CA Cos.
	County	State	County	State	Co. vs. State	95% CI	
1988-89	493.3	458.5	8234	221273	1.0760	-	7
1990-94	500.5	479.4	23340	617355	1.0440	0.004-0.108*	12
1995-99	476.7	464.1	24662	650039	1.0272	0.021-0.076*	17
2000-04	466.9	451.3	27411	702339	1.0346	0.014-0.069*	15
2005-09	453.6	437.9	29664	750630	1.0359	0.013-0.067*	22
1990-09	472.7	456.8	105077	2720263	1.0349	0.016-0.066*	14

*Significant at $P < 0.05$

Table 5: Annual Incidence Rates (SIR), All Invasive Cancers Combined (Adjusted to 2000 U.S. Standard Population, Sacramento County vs. California (Standard Incidence Ratio), 1988-1989 vs. 1990-2009, stratified by Gender).

Period	Cases/100,000		Cancer Cases		SIR		95% CI
	County	State	County	State	Co. vs. State		
Males	1988-89	571.4	542.6	3997	111846	1.0532	
	1990-09	556.1	537.2	53511	1403063	1.0353	
	Change in SIR					-0.0179	-0.019-0.055
Females	1988-89	454.4	409.6	4237	109427	1.1093	
	1990-09	417.6	402.6	51586	1317200	1.0372	
	Change in SIR					-0.0721	0.036-0.108*

*Significant at $P < 0.05$

Table 6: Annual Incidence Rates, All Invasive Cancers Combined (Adjusted to 2000 U.S. Standard Population; Sacramento County vs. California (Standard Incidence Ratio, SIR); 1988-1989 vs. 1990-2009; stratified by Race).

Period	Cases/100,000		Cancer Cases		SIR		95% CI
	County	State	County	State	Co. vs. State		
White, Non-Hispanic	1988-89	514.9	490.3	6864	175098	1.0501	
	1990-09	503.5	496.6	80769	1926329	1.0139	
	Change in SIR					-0.0362	0.009-0.063*
Black, Non-Hispanic	1988-89	512.9	499.8	467	13300	1.0262	
	1990-09	492.9	510.4	7790	172870	0.9657	
	Change in SIR					-0.0606	-0.048-0.169
Asian/Pacific Islander, Non-Hispanic	1988-89	321.7	319.9	123	10164	1.0056	
	1990-09	312.6	320.0	7599	208583	0.9769	
	Change in SIR					-0.0287	-0.087-0.144
Hispanic	1988-89	426.7	328.6	458	20821	1.2986	
	1990-09	374.6	348.7	7454	365721	1.0744	
	Change in SIR					-0.2242	0.086-0.362*

*Significant at $P < 0.05$

In the period 1988-1989, Sacramento County had a Standard Incidence Ratio (compared to the state of California) of 1.0760, based on 8234 diagnosed cases. Steadily decreasing

SIRs followed in the two five year periods (1.0440 and 1.0272), then there was a leveling-off to 1.0346 and 1.0359. In the most recent period (2005-2009), the Sacramento rate had fallen to the 22nd highest in the state, down from 7th two decades earlier. Each of the four SIRs following the Rancho Seco shutdown, plus the 20-year period 1990-2009, was significantly different from that of 1988-1989. When the SIRs from 1988-1989 and 1990-2009 were compared, 4.11% fewer cancer cases than expected were diagnosed in the latter period among Sacramento County residents. Based on 105,077 actual cancer cases in the 20 year period, this difference represents 4,319 fewer persons diagnosed with cancer in the county than if the 1.0760 SIR of 1988-1989 had been unchanged.

Cancer by Gender: Table 5 shows the change in SIR for cancer incidence in Sacramento for each gender. Declines in Sacramento County cancer SIR were observed for both males and females. The change was four times greater in females than in males, so it was statistically significant only for females. Over the past two decades, Sacramento's male and female SIRs were nearly equal (1.0353 and 1.0372).

Cancer by Race/Ethnicity: Table 6 shows the change in SIR for cancer incidence in Sacramento for each racial/ethnic group. The California Cancer Registry divides race into Hispanics and non-Hispanic whites, non-Hispanic blacks, and non-Hispanic Asian/Pacific Islanders, jointly accounting for about 99% of the state's population. The SIR decreases for each of the four racial/ethnic groups were significant for Hispanics and white non-Hispanics. These two groups account for about 85% of all cancers in California and Sacramento County. Of particular note is the dramatic decline in SIR for Hispanics, from a high of 1.2986 in 1988-1989, based on 458 cases. The Hispanic SIR continued to decline in the 1990s (1.0932) and the 2000s (1.0676). Hispanics represent the fastest-growing segment of the population in both the state and county.

Cancer by Most Common Type: Table 7 presents the change in the county vs. state SIR for each of the 16 most common types of cancer diagnosed in California. These account for 88% of all invasive cancers diagnosed in the state and county. Declines in SIR were observed for 13 of the 16 most common cancers during the two decades after Rancho Seco shutdown. Of these, four were statistically significant decreases while two more were of borderline significance. Of the three types of cancer showing an increase in SIR (lung/bronchus, corpus uteri, and stomach), all were relatively slight increases and none approached statistical significance. Among the four types of cancer with a significantly decreased SIR were cancers of the female breast and thyroid (The change for female breast cancer in situ was borderline significant). These malignancies were found to have the highest excess relative risk among Hiroshima and Nagasaki survivors from 1958 to 1987.²⁵ In particular, radioactive iodine produced only in nuclear weapons tests and nuclear reactor emissions is easily the best-recognized risk factor for thyroid cancer.²⁶⁻²⁷ Thus, the thyroid cancer SIR would be expected to decline as intake of radioiodine is reduced. Table 8 shows the SIR for Sacramento County vs. California for thyroid cancer during the five-year periods after Rancho Seco shutdown.

In California, as in all U.S. states, thyroid cancer incidence has risen rapidly since the 1980s. But the Sacramento County rate in the 1990s remained slightly below that of 1988-1989, when Rancho Seco was still in operation. Thus, the SIR experienced a sharp decline after that time, from 1.2722 to 1.1756 to 1.0341. After 2000, the thyroid cancer SIR fell below 1.0, meaning the county rate had fallen below that of the state, a major departure from the late 1980s. When the SIR for each five year period after shutdown was compared to

1988-1989, the decline over the last two five year periods (2000-04 and 2005-09) was statistically significant.

Cancer Incidence Among Children: Because the developing fetus and infant are most susceptible to cellular damage from exposure to radiation, cancer in children has been the most-studied type of malignancy in investigations of health risk from nuclear plants. Childhood leukemia, which accounts for just under one-third of childhood cancer cases, has been a particular focus, but all-cancer incidence and mortality among children living near nuclear plants also show unexpectedly elevated levels, as illustrated in Table 1.

Table 7: Annual Incidence Rates, Most Commonly Diagnosed Invasive Cancers (Adjusted to 2000 U.S. Standard Population; Sacramento County vs. California (Standard Incidence Ratio); 1988-1989 vs. 1990-2009; stratified by cancer type).

	Period	Cases/100,000		Cancer Cases		SIR	
		County	State	County	State	Co. vs. State	95% CI
Female breast invasive	1988-89	142.60	127.93	1312	33469	1.1147	
	1990-09	132.52	128.05	16219	414647	1.0349	
	Change in SIR					-0.0798	0.022-0.152*
Male prostate	1988-89	136.85	132.08	873	25211	1.0361	
	1990-09	164.47	160.98	15632	413771	1.0217	
	Change in SIR					-0.0144	-0.063-0.092
Lung and bronchus	1988-89	79.18	69.08	1323	33227	1.1463	
	1990-09	69.52	59.34	15197	346399	1.1716	
	Change in SIR					+0.0254	-0.093-0.042
Colorectal	1988-89	62.05	57.11	984	26530	1.0850	
	1990-09	48.34	48.61	10567	283914	0.9944	
	Change in SIR					-0.0906	0.018-0.166*
Urinary bladder	1988-89	23.64	20.79	382	9790	1.1371	
	1990-09	20.46	19.77	4437	114663	1.0349	
	Change in SIR					-0.1022	-0.023-0.227
Non-Hodgkin lymphoma	1988-89	16.61	16.74	285	8174	0.9922	
	1990-09	18.31	18.80	4094	113903	0.9736	
	Change in SIR					-0.0186	-0.108-0.145
Melanoma of the skin	1988-89	17.60	13.60	325	6973	1.2941	
	1990-09	19.34	17.92	4424	109619	1.0792	
	Change in SIR					-0.2149	0.060-0.370*
Female breast cancer in situ	1988-89	20.39	15.60	188	3970	1.3071	
	1990-09	27.91	25.14	3392	80635	1.1102	
	Change in SIR					-0.1969	-0.006-0.400**
Leukemia	1988-89	11.96	12.54	207	6192	0.9537	
	1990-09	11.23	12.31	2543	74857	0.9123	
	Change in SIR					-0.0414	-0.103-0.185
Female corpus uteri	1988-89	23.07	23.78	217	6383	0.9701	
	1990-09	22.17	22.49	2718	72904	0.9858	
	Change in SIR					+0.0157	-0.157-0.126
Oral cavity and pharynx	1988-89	15.60	12.30	261	5984	1.2683	
	1990-09	12.04	10.88	2695	65396	1.1066	
	Change in SIR					-0.1617	-0.008-0.331**
Kidney and renal pelvis	1988-89	10.52	9.44	173	4531	1.1144	
	1990-09	12.12	11.47	2703	68548	1.0567	
	Change in SIR					-0.0577	-0.124-0.240
Pancreas	1988-89	13.40	11.53	215	5368	1.1622	
	1990-09	11.79	11.15	2563	64869	1.0574	
	Change in SIR					-0.1048	-0.067-0.276
Stomach	1988-89	8.76	10.29	143	4806	0.8513	
	1990-09	7.68	8.72	1683	51190	0.8807	
	Change in SIR					+0.0294	-0.184-0.126
Thyroid	1988-89	6.45	5.07	126	2771	1.2722	
	1990-09	7.69	7.52	1837	48391	1.0226	
	Change in SIR					-0.2496	0.001-0.498*
Female Ovary	1988-89	14.41	15.71	135	4179	0.9173	
	1990-09	12.62	13.82	1555	45064	0.9132	
	Change in SIR					-0.0041	-0.167-0.175

*Significant at $P < 0.05$; **Borderline significant

Table 8: Annual Incidence Rates, Thyroid Cancer (Adjusted to 2000 U.S. Standard Population; Sacramento County vs. California (Standard Incidence Ratio, SIR); 1988-1989 vs. Subsequent Five-Year Periods).

Period	Cases/100,000		Cancer Cases		SIR	
	County	State	County	State	Co. vs. State	95% CI
1988-89	6.45	5.07	126	2771	1.2722	-
1990-94	6.36	5.41	332	7829	1.1756	-0.178-0.372
1995-99	6.36	6.15	360	9478	1.0342	-0.030-0.506
2000-04	7.32	7.58	460	12742	0.9657	0.042-0.571*
2005-09	10.09	10.25	685	18342	0.9844	0.041-0.534*
1990-09	7.69	7.52	1837	48391	1.0226	0.001-0.498*

*Significant at $P < 0.05$

Table 9: Annual Incidence Rates, All Cancers, Children 0-19 (Sacramento County vs. California (Standard Incidence Ratio, SIR); 1988-1989 vs. Subsequent Five-Year Periods).

Period	Cases/100,000		Cancer Cases		SIR	
	County	State	County	State	Co. vs. State	
1988-89	17.92	15.81	104	2687	1.1335	
1990-94	15.49	15.83	257	7318	0.9782	
1995-99	14.67	15.50	265	7742	0.9469	
2000-04	14.77	16.35	287	8519	0.9035	
2005-09	17.75	17.25	356	9115	1.0392	
1990-09	15.71	16.26	1165	32694	0.9667	

The California Cancer Registry has collected age at diagnosis for each case reported. Table 9 presents the Sacramento County SIR for the last two years of Rancho Seco operation for children age 0-19 years, along with the SIR for each of the subsequent four periods of five years each.

From 1988-1989 to 1990-1994, the Sacramento County child cancer rate fell from 17.92 to 15.49 cases per 100,000 population, a drop of 11.7%, while the state rate remained virtually unchanged. Over the next two five year periods the county rate continued to decline before rising in 2005-2009 (to a level still lower than in the late 1980s). The county/state SIR fell from 1.1335 to 0.9667 in the two decades following Rancho Seco shutdown. The sharp decline in the Sacramento County SIR for child cancer was consistent for both age 0-9 (1.1437 to 1.0096) and age 10-19 (1.1201 to 0.9215). Statistical significance was not calculated for child cancers as the California Cancer Registry did not provide confidence intervals for incidence rates.

DISCUSSION

The shutdown of nuclear plants and the reduction of radioisotope levels in the environment and diet suggest that reductions in local rates of radio-sensitive diseases such as cancer will also occur. While there is evidence of short-term reductions after shutdown in rates of disorders affecting the fetus and infant,^{13,14} no review of long-term rate changes in the entire population has yet been undertaken.

The extensive length of time since shutdown of many U.S. reactors, along with the existence of historical databases of local health status, makes long-term trend analysis possible. This report focuses on the Rancho Seco nuclear plant in Sacramento County, California. The reasons for selecting Rancho Seco are multiple: the plant was closed on June 6, 1989, which provides a long post-shutdown period to examine; the state cancer registry maintains county-specific incidence data since before the plant closed; and the plant is located

close to a large metropolitan area, which will increase the likelihood of statistical significance for any changes in health.

After Rancho Seco closed, a number of statistically significant declines in Sacramento County's Standard Incidence Ratio (compared to the state of California) were observed. These included all cancers combined; females; white non-Hispanics and Hispanics; six of the 16 most common types of cancer; and radiosensitive breast cancer and thyroid cancer. Declining SIRs were observed for 28 of 31 groups evaluated; of the 28 declines, 14 were statistically significant and two more were borderline significant. In general, the sharpest declines in SIR occurred during the 1990s, the first decade after reactor closure. An estimated 4,319 fewer cases of cancer were diagnosed in Sacramento County in the 20-year period 1990 to 2009 because of the reduction in the local SIR.

Significant reductions in cancer SIR for Sacramento County were observed for many, but not all, of the categories with relatively large numbers of cases. One exception to this pattern is that SIR reductions during the 20 years after Rancho Seco shutdown were significant for females but not for males. More detailed analysis is needed to explain this dichotomy.

While these findings are noteworthy, more evaluation is needed before it can be concluded that the correlation documented between reduced exposure to radiation and cancer risk indicates a cause-effect relationship. Because the topic of long-term changes in local health status was virtually unexamined until this report, a variety of other approaches could be taken, including:

- Expand the Rancho Seco analysis to include most proximate downwind counties;
- Conduct an analysis of cancer mortality similar to that of incidence;
- Examine changes in age-specific health status, aside from children;
- Add information on changes in *in-vivo* radiation doses over time;
- Examine temporal trends from registries of other diseases, e.g., prematurity, autism;
- Examine temporal trends in other forms of toxic chemicals in the local environment;
- Duplicate the Rancho Seco analysis near other closed reactors;
- Address the potential effects on health data of immigration and emigration in an area;
- Address whether two years of data (in this case, 8234 cancer cases) represent an adequate baseline period.

One important point raised by this report is the potential health impact of relatively low levels of radioactivity. This topic has been considered for decades and early assumptions that exposure below a certain dosage caused no harm were contradicted by a number of studies. Beginning in the late 1950s, the first reports documenting a near-doubling of risk of death from cancer to fetuses whose mothers received abdominal X-rays during pregnancy were published.²⁸⁻³⁰ In the late 1990s, the U.S. National Cancer Institute estimated the internal doses of Iodine-131 from above-ground Nevada nuclear weapons tests for each U.S. county,³¹ which served as the basis for the estimate that up to 212,000 Americans developed thyroid cancer from exposure to this isotope.³² In the year 2000, the U.S. Energy Department published a compendium of studies concluding that occupationally exposed workers at nuclear weapons plants were more likely to develop many forms of cancer later in life.³³ A more recent report concluded that exposure to atom bomb test fallout in Europe and the USA, Chernobyl emissions in Europe and parts of Asia, and emissions from nuclear power plants in Germany and Switzerland increased the human sex odds (ratio of male

births to female births).³⁴ These, and other studies, served as the basis for blue-ribbon panels to conclude that the linear no-threshold model probably best describes the relationship between radiation exposure and health risk.³⁵

More recently, several reports have been issued that questioned existing methods used to estimate dose, and thus health casualties of radiation exposure. In 2003, a European expert panel challenged the current internal dose model of the International Committee on Radiation Protection.³⁶ Other reports calculated that doses from internal radiation sources could have been underestimated by 10- to 100-fold.^{37,38} The continuing debate over radiation dose-response models should be considered when a phenomenon such as changes in local health after a nuclear plant closes is evaluated.

For years, reports documenting elevated rates of child cancer incidence near operating nuclear power plants have been published. Eleven of these, each representing a separate plant, examined nuclear facilities in the United Kingdom.³⁹⁻⁴⁹ Similar results were obtained in reports near reactors in Turkey, Canada, France, Germany, and Kazakhstan.⁵⁰⁻⁵⁴ One study in the U.S. found that all 14 areas near nuclear plants in the eastern U.S., cancer incidence age 0-9 from 1988-1997 exceeded the U.S. rate.⁵⁵ The aforementioned were descriptive studies, but in the past four years, more sophisticated and more comprehensive case-control studies of all reactors in Germany⁵⁶ and France⁵⁷ have revealed significantly elevated rates of leukemia in young children living in areas proximate to nuclear sites. The state of the art in understanding dose changes from nuclear reactor emissions and their effects on human health continues to evolve.

There is currently an intense debate on the future of nuclear power plants. For a long time, costs and energy needs were the primary foci of the dialogue, but since the March 11, 2011 debacle at Fukushima, the paramount issue has become safety and health. Within two months of the meltdown, the Japanese government closed all but 17 of that nation's 54 nuclear reactors, with the rest undergoing safety inspections and upgrades.⁵⁸ On May 5, 2012, the last of the 54 reactors closed, leaving Japan with no nuclear power for the first time in over four decades.⁵⁹ In July 2012, two reactors at the Ohi plant were restarted; but by January 2013, these were the only operating reactors in the nation.⁶⁰

The government of Germany closed seven reactors soon after Fukushima, and plans phase-out of its other 17 by 2022. Belgium announced a phase-out of seven reactors by 2025. Switzerland cancelled plans for three new reactors, then announced a phase-out of its five reactors by 2033. Italy, which has no nuclear power plants, cancelled plans to bring new reactors online. Finally, Francois Hollande, elected French president in May 2012, campaigned on a pledge to reduce nuclear power's 77% share of the electrical market by half by 2030.⁶¹

The 104 aging U.S. reactors at 65 plants affect many Americans. According to the 2010 U.S. Census, over 18 million Americans live within 20 miles of a nuclear power plant, and over 116 million live within 50 miles.⁶² The potential effects of locating these reactors should not be measured only in terms of health, but also of cost. For example, the 4319 fewer cancers than expected in Sacramento County during the first 20 years after the Rancho Seco closure translates into many millions saved in direct medical costs, reduction of productivity lost, and additional savings associated with the value of a human life. With large numbers such as these, and with the future of this source of power a matter of great

public concern, reports like this one must be followed by similar efforts to attain better understanding of potential improvements in public health after reactor shutdown.

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COMPETING INTERESTS

The authors declare that they have no conflict of interest in connection with this publication.

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