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Strontium-90 in Baby Teeth as a Basis for Estimating U.S. Cancer Deaths From Nuclear Weapons Fallout

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Abstract

Nuclear weapons testing in the atmosphere during the 1950s and 1960s deposited fallout throughout the world, exposing all humans to food and water before the Limited Test Ban Treaty ended large-scale tests. The largest effort to measure in vivo fallout in humans, performed by Washington University (USA), collected over 300,000 deciduous teeth to document a sustained increase in Strontium-90 (Sr-90) during testing and a sharp decline after the test ban. Sr-90 patterns and trends in teeth were consistent with those of bones and milk. Sr-90 is still detectable in about 100,000 of the teeth, which were never tested. Tooth donors were born during atmospheric testing (1946–1965) and thus exposed to fallout in utero and during infancy/childhood, when exposures pose the greatest health risk. Preliminary analysis of global fallout's health risk in the United States indicates recent cancer mortality in several high-fallout areas exceeded that of states with the lowest fallout, peaking for the cohort born in the early 1960s, when fallout was highest. These findings support subsequent measurement of Sr-90 in deciduous teeth of persons who died of diseases such as cancer, along with controls, a novel approach to assessing fallout hazards.

Keywords

nuclear weapons, bomb fallout, radioactivity, Strontium-90, deciduous teeth

Since 1945, a total of 2,056 nuclear weapons tests have been conducted by eight nations, 528 of which were in the atmosphere and under water. These 528 detonations included 215 by the United States, 219 by the Soviet Union, 50 by France, 23 by China, and 21 by the United Kingdom. The last large-scale tests occurred in 1963, with only China and France testing above the ground thereafter. The latest atmospheric test occurred in 1980.[1–3]

Atmospheric weapons test yield from 1945 to 1980 was 428 megatons, equal to 29,000 Hiroshima bombs.[4] Detonations in the northern Hemisphere included those by the United States, Soviet Union, United Kingdom, France, and China. The only tests in the southern hemisphere were conducted by France and the United Kingdom.

Each atmospheric test resulted in the production of large amounts of fallout, consisting of about 200 radioactive isotopes.[5] Radioactive particles and gases from bomb tests propelled into the stratosphere moved through prevailing winds and returned to Earth through precipitation. Deposition of fallout into food and water resulted in humans and animals ingesting these isotopes. Fallout was dispersed to all areas of the earth.[6]

Continued testing generated interest in the buildup of fallout in human bodies. In August 1958, Herman Kalckar of the (U.S.) National Institutes of Health proposed an international milk tooth (deciduous tooth) census to understand the extent of fallout's increase. Kalckar suggested that radioactive Strontium-90 (Sr-90) concentrations in deciduous teeth be measured, for multiple reasons, namely:

- The natural loss of teeth made sample collection relatively simple
- Analysis of children focused on those most susceptible to radioactive exposure

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- The slow decay rate of Sr-90 meant it remained in the body for a lifetime and can be measured long after initial exposure[7]

Sr-90 is chemically similar to calcium and is taken up in bone and teeth after ingestion. Approximately half of the Sr-90 ingested from bomb test fallout was through milk, with the other half through cereal and vegetables.[8]

Officials in multiple nations enacted programs measuring Sr-90 in deciduous teeth. These nations included Denmark/ Faroes Islands/Greenland,[9,10] England/Wales,[11] Finland,[8,12] Hungary,[13] Italy,[14] Japan,[15] Romania,[16] Slovakia,[17] and the United States.[18–20]

In each nation, steady increases in Sr-90 concentrations in children's teeth were observed throughout the 1950s and the early 1960s, followed by sharp declines almost immediately after the cessation of large-scale atmospheric testing.[19–21] Decades after the ban on atmospheric testing, Sr-90 from fallout had essentially disappeared from the biosphere. Average concentrations in precipitation samples in Finland fell from 399.0 to 0.61 becquerels Sr-90 per gram calcium from 1963 to 1985, and further to 0.28 in 2005.[22] *In vivo* Sr-90 from fallout also approached zero; for example, baby teeth in Switzerland showed a decline from 421 to 30 becquerels Sr-90 per gram calcium from persons born in 1963 versus 1994.[23]

In the United States, the earliest program measuring *in vivo* trends of bomb fallout concentration began in 1953, as officials from the Atomic Energy Commission measured Sr-90 in human bone.[24] The program also included rain, food, and milk; by 1962, over 10,000 human samples had been collected worldwide.[25] Temporal trends of Sr-90 in bone were similar to those in deciduous teeth.[26–31] Studies of Sr-90 levels in bone ended in 1982, the last official American program measuring *in vivo* radioactivity levels.[32]

Sr-90 concentrations in U.S. deciduous teeth were studied from 1958 to 1970 in a combined effort by scientists and citizens based in St. Louis. Over 300,000 teeth were collected, and large increases in Sr-90 levels were documented through 1964. Average Sr-90 in mandibles of stillborn births in St. Louis declined by about half from the 1964 peak to 1968.[19] Although Sr-90 was just one of many radioisotopes in bomb test fallout, it can serve as a relatively strong proxy for temporal and spatial patterns of all long-lived isotopes.

Carcinogenicity of Sr-90 has long been recognized. During the Manhattan Project in World War II, consideration was given to contaminating the food supply in Germany with radioactive strontium.[33] Published studies confirmed the Sr-90/cancer association in mice,[34] rabbits,[35] rats,[36] swine,[37] and dogs.[38, 39] Radioactive strontium may cause cancer in humans as a result of damage to genetic material in cells.[40]

Exposures to carcinogens may increase cancer risk even at relatively low-dose exposures. Adverse health effects from low-dose radioactivity have been documented.[41–43] The linear no-threshold dose-response relationship between radiation exposure and health risk is consistently observed in many studies. A blue-ribbon panel of the U.S. National Academy of Sciences issued several detailed reports based on hundreds of peer-reviewed studies, upholding the consistent pattern of the linear no-threshold dose-response relationship between exposure and health risk.[44]

Biological effects of low-dose Sr-90 have been studied. Small amounts of Sr-90 injected into rats led to a depression of cellularity in bone marrow.[45] Chronic exposure of low-dose Sr-90 in rats can induce functional changes in bone marrow stromal cells, which may explain subsequent adverse health effects.[46]

To date, few studies of health risk using in-body levels of radioactivity have been conducted. Studies comparing Sr-90 in bones of persons with cancer versus healthy controls were inconclusive and hampered by small sample sizes and lack of comparability.[47–49]

Early-life exposure to a particular dose of radiation is considerably more hazardous than the same dose in adults, but published reports documenting this excess risk have been limited. In the United States, a five-year lag between Sr-90 exposure and elevated leukemia mortality in children ages five to nine, along with a correlation of regional differences in leukemia rates with Sr-90 in food, has been documented.[50] The only published U.S. study of cancer and in-body radioactivity was a case-control study of 60 St. Louis-area incisor teeth from males born 1958–1960; average Sr-90 concentration of teeth in persons who died of cancer prior to age 50 more than doubled the average of those who reported no major diseases at age 50 ($p < 0.04$).[51]

Official estimates of cancer risk to Americans from atmospheric bomb test fallout included: (*a*) 11,300 to 212,000 (median 75,000) cases of thyroid cancer[52] and (*b*) 11,000 cancer deaths.[53] Both studies, which assessed those born during the 1950s and 1960, were based on Iodine-131 milk deposition estimates from Nevada atmospheric tests.[54, 55]

In the St. Louis-based study, led by citizens and researchers from Washington University, about 100,000 of the (more than) 300,000 deciduous teeth collected were not tested for Sr-90 concentration and have been preserved for over fifty years. These 100,000 teeth represent 37,000 persons (some provided multiple teeth) born from 1946 to 1965. Many were born in the St. Louis area, but teeth from those born in all fifty U.S. states plus forty five other nations are included. Each tooth was secured in envelopes after the initial donation. Data on each tooth and donor generated by parents and dentists, which originally were indicated on 3 × 5 cards, were recently automated.

The existence of this database represents a unique opportunity to analyze the health effects of global atmospheric nuclear weapons tests. Tooth donors were born between fifty-five and seventy-five years ago, and Sr-90 (and other long-lived isotopes such as cesium and plutonium) is still detectable, making possible a long-term longitudinal study assessing relative levels in deciduous teeth and health patterns later in life. Public health databases such as death registries offer a basis for generating data on health status. This report assesses early life exposure—observed in milk and deciduous teeth—to bomb test fallout among Americans born during testing and presents initial data addressing health patterns in this population.

Materials and Methods

The cohort of Americans born in the 1950s and 1960s, who donated deciduous teeth to the Washington University study, is most likely to experience adverse health effects from fallout later in life. This cohort incurred exposures during the fetal, infant, and childhood periods when health risk from a dose of radiation is most elevated.[56]

This report begins a broad assessment of bomb fallout's health risks. Both temporal and spatial analyses of exposure to Sr-90 were performed, for persons born in the St. Louis area and for the entire United States. Levels of dietary (milk supply) and in-body (deciduous teeth) concentrations of Sr-90 were available, providing a means of understanding deposition patterns in human bodies of all long-lived radionuclides in fallout.

The U.S. Public Health Service program of measuring radionuclide levels in milk commenced in mid-1957, with monthly samples reported for five cities, including St. Louis. The program was expanded to 60 cities in 1960 and to 120 cities in 1967.[57–59] Sr-90 in milk can be used to quantify both temporal trends and spatial differences in uptake.

Average Sr-90 concentrations in pasteurized milk during the third quarter (1960 to 1967) or for twelve-month periods ending in September (1968 to 1973) were available.

Table 1. Average Annual Picocuries Strontium-90 (Sr-90) per Liter Pasteurized Milk in the United States, 60 Cities, by Years 1960–1973.

Year	Sr-90
1960	7.22
1961	8.27
1962	14.65
1963	28.32
1964	22.13
1965	15.30
1966	12.58
1967	10.00
1968	9.00
1969	7.76
1970	6.94
1971	6.94
1972	6.21
1973	4.64

Source: U.S. Public Health Service.[57–59]

Three months represented a relatively accurate proxy of an entire year, for a slow-decaying radioisotope such as Sr-90, and thus were useful for this analysis.

The St. Louis-based deciduous tooth study provided the most comprehensive *in vivo* database of fallout and was used as a proxy for temporal trends in Sr-90 uptake. Data on *in vivo* Sr-90 trends in St. Louis infants born from 1964–1970 were generated using mandibles from stillborn infants, making possible an analysis of trends in Sr-90 after cessation of large-scale nuclear weapons tests. Analysis of Sr-90 in teeth of persons born after 1963 was not possible, as teeth were shed in the 1970s, after collection and testing of baby teeth ceased.[20]

This report considered potential later-life health risk from exposure to fallout in the cohort studied. Recent cancer mortality, using official data,[60] were compared in areas of the United States with the lowest bomb fallout levels in milk versus the rest of the United States. We propose two hypotheses: (*a*) the risk of dying of cancer later in life in relatively low-fallout states will be less than that of the nation and (*b*) excess mortality will be greatest in the cohort born when concentrations of Sr-90 in milk and deciduous teeth was highest.

Results

Sr-90 in Milk—Temporal Trends

The U.S. government program measuring radionuclides in pasteurized milk was the basis for trends in radioactivity uptake. Table 1 and Figure 1 show the average national concentration of Sr-90 for each year from 1960 to 1973; empirical data are provided in Appendix A. Information from 60 monitoring stations in the United States that reported data in each of the 14 years were included. Measurements were expressed in average picocuries—the standard unit of radioactivity used in the United States—of Sr-90 per liter of milk, and the number of monitoring stations reporting data were also given.

A steady increase in average Sr-90 in milk occurred from 1960 (7.22) before peaking in 1963 (28.32), as the ban on

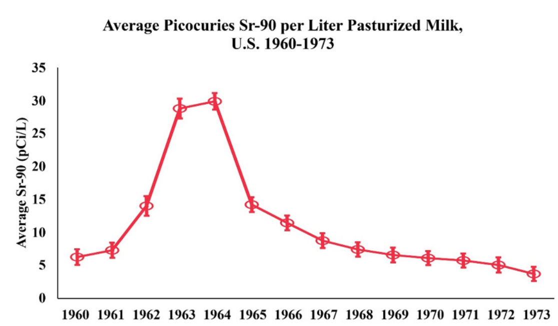


Figure 1. Average strontium-90 (Sr-90) in pasteurized milk by birth cohorts in the U.S., 1960-1973[19].

atmospheric nuclear tests went into effect. Thereafter, levels plunged by nearly one-half over the next two years. By 1973, the average Sr-90 level had dropped to 4.64, down 84 percent from the peak of a decade earlier.

Sr-90 in Deciduous Teeth—Temporal Trends

The Washington University study of Sr-90 in deciduous teeth calculated an annual average concentration from 1950 to 1963 for each type of tooth, namely incisors, first molars, second molars, and cuspids. It also extrapolated Sr-90 in teeth based on temporal trends found in mandibles of stillbirths from 1964 to 1970. Table 2 and Figure 2 present annual (1950–1970) averages for incisors, in persons born in the St. Louis area, in picocuries of Sr-90 per gram of calcium.

From a level near zero for 1950 births (0.165 picocuries per gram calcium), annual Sr-90 averages increased steadily until 1960, followed by a modest decline over the following two years, as a moratorium in above-ground testing was observed by the United States and Soviet Union from September 1958 to September 1961. After testing resumed, averages increased sharply, peaking at 10.453 for 1964 births (63 times greater than 1950), followed by a steady decrease of over 50 percent thereafter; similar patterns occurred for molars and cuspids.[21]

Highly significant difference in Sr-90 levels were observed among cohorts for incisors and all tooth types (Incisors F = 12.4, d.f. = 4,17, $p < 0.0001$; Second Molars: F = 11.3, d.f. = 4,17, $p < 0.0001$; First Molars: F = 12.1, d.f. = 4,17, $p < 0.0001$; Canines: F = 11.4, d.f. = 4,17, $p < 0.0001$). No significant differences were observed among tooth types (F = 1.18, d.f. = 3,3, $p < 0.33$), as the amount Sr-90 uptake is relatively similar regardless of tooth type.

Table 2. Average Picocuries Strontium-90 (Sr-90) per Gram Calcium Incisor Deciduous Teeth Births in St. Louis Area, 1950–1970.

Year	Sr-90
1950	0.165
1951	0.328
1952	0.453
1953	0.562
1954	0.727
1955	0.850
1956	1.015
1957	2.551
1958	2.730
1959	4.719
1960	5.446
1961	5.171
1962	3.896
1963	6.543
1964	10.453
1965	9.575
1966	8.354
1967	6.612
1968	4.348
1969	5.048
1970	5.556

Source: Cua, 1992.[21]

Sr-90 in Milk- Spatial Patterns

The similarity in U.S. trends of Sr-90 in milk and deciduous teeth corresponds to other analyses of Sr-90 showing similar patterns in milk, soil, and precipitation.[61] Within the United States, spatial patterns may vary, as atmospheric fallout was carried by prevailing winds and returned to Earth through precipitation. Thus, geographic distribution of radioactivity levels in the food supply and the body is highly dependent on these two vectors. Appendix A provides 1960–1973 annual averages of Sr-90 in pasteurized milk for each of the sixty sites in the United States reporting data each year.

Using nine standard geographic regions of the United States, as shown in the map in Figure 3, the significance of spatial variation of Sr-90 in milk was analyzed. Figure 4 plots least squares means (+/− one standard error) for each region in each year 1960–1971. ANOVA tests revealed highly significant differences among regions for all years ($p < 0.001$) except for 1963 ($p = 0.043$) and 1964 ($p = 0.031$) when variances among cities within regions were high. Figure 5 plots least squares means (+/− one standard error) for each year showing temporal changes within regions from 1960 to 1973. ANOVA tests are highly significant among years ($p < 0.0001$) for all regions.

The area least affected by bomb fallout includes the contiguous states of Arizona, California, and New Mexico, on

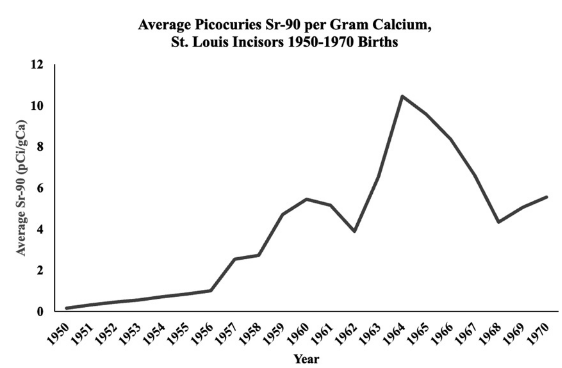
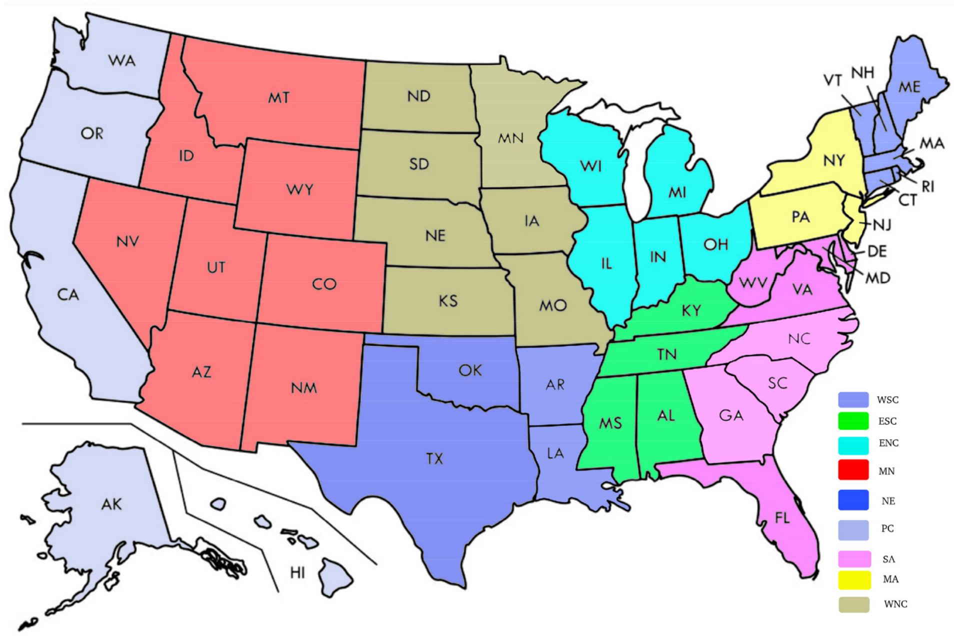


Figure 2. Average Strontium-90 (Sr-90) concentration in teeth by birth cohorts in the St. Louis area, 1951–1970. Reported as pCi Sr-90 per gram calcium (± 1 SE). There were highly significant differences in Sr-90 levels among cohorts for all tooth types (Incisors F = 12.4, d.f. = 4,17, $p < 0.0001$; Second Molars: F = 11.3, d.f. = 4,17, $p < 0.0001$; First Molars: F = 12.1, d.f. = 4,17, $p < 0.0001$; Canines: F = 11.4, d.f. = 4,17, $p < 0.0001$) but no significant differences among tooth types (F = 1.18, d.f. = 3,3, $p < 0.33$).
Source: Rosenthal, 1969 .[20].



Map of the U.S. showing regions grouped for analysis. **PC** = AK, CA, HI, OR, & WA; **MN** = MT, ID, WY, NV, UT, CO, AZ & NM; **WNC** = ND, SD, MN, IA, NE, KS & MO; **ENC** = WI, MI, IL, IN & OH; **NE** = CT, MA, ME, NH, RI & VT; **SA** = WV, MD, DE, VA, NC, SC, DC, GA & FL; **ESC** = KY, TN, MS & AL; **WSC** = OK, AR, LA & TX; **MA** = PA, NJ & NY.

Figure 3. United States, by region. Map of the United States showing regions grouped for analysis. **PC** = AK, CA, HI, OR, and WA; **MN** = MT, ID, WY, NV, UT, CO, AZ ,and NM; **WNC** = ND, SD, MN, IA, NE, KS, and MO; **ENC** = WI, MI, IL, IN & OH; **NE** = CT, MA, ME, NH, RI, and VT; **SA** = WV, MD, DE, VA, NC, SC, DC, GA, and FL; **ESC** = KY, TN, MS, and AL; **WSC** = OK, AR, LA, and TX; **MA** = PA, NJ, and NY.

the Pacific coast and southwest United States. Relatively low levels of environmental fallout reflected wind and precipitation patterns. None of the three states are located downwind (east) of the Nevada Test Site, where 100 of the 215 atmospheric tests occurred, and precipitation levels are low relative to the rest of the United States. Milk monitoring stations were located in Albuquerque, New Mexico; Sacramento, California; San Francisco, California; and Tucson, Arizona, with an average annual Sr-90 concentration in milk of 3.17, versus 11.95 for the other fifty-seven U.S. sites reporting milk data each year from 1960 to 1973.

Subsequent Cancer Mortality by Birth Cohort—Low-Fallout Area Versus Other United States

Identifying an area with the lowest Sr-90 levels—and thus, of all slow-decaying radionuclides present in fallout—in the environment (milk) raises the issue of whether later-life health outcomes in the area for those born during bomb testing differed from the rest of the United States. As isotopes present in fallout are carcinogenic and affect multiple organs, mortality of all cancers combined was analyzed.[60]

Table 3 shows differences in mortality rates in the two-year period 2019–2020 for those born during bomb testing for all neoplasms (cancers) combined, comparing the low-fallout area of Arizona, California, and New Mexico with the rest of the United States. Cohorts for those born during testing were analyzed, including those born 1945–1949 (died at age 70–74), born 1950–1954 (died at age 65–69), born 1955–1959 (died at age 60–64), and born 1960–1964 (died at age 55–59).

The analysis includes white non-Hispanics and black non-Hispanics, which account for slightly less than 90 percent of the 2019–2020 cancer deaths in the United States among persons aged 55 to 74. Other groups, mostly Hispanics and Asians, included decedents who were likely born outside the United States, in areas where bomb test fallout was considerably lower, and thus were excluded.

A consistent increase in the standard mortality ratio of other U.S. versus the three states was observed for each successive birth cohort, starting from 1945–1949 up to 1960–1964. Ratios were 1.102, 1.116, 1.167, and 1.210 for white non-Hispanics and 0.989, 1.003, 1.033, and 1.143 for black non-Hispanics. Confidence intervals showing the differences in the youngest two cohorts, born 1955–1959 and 1960–1964, were significantly different from the expected (the ratio for the 1945–1949 cohort).

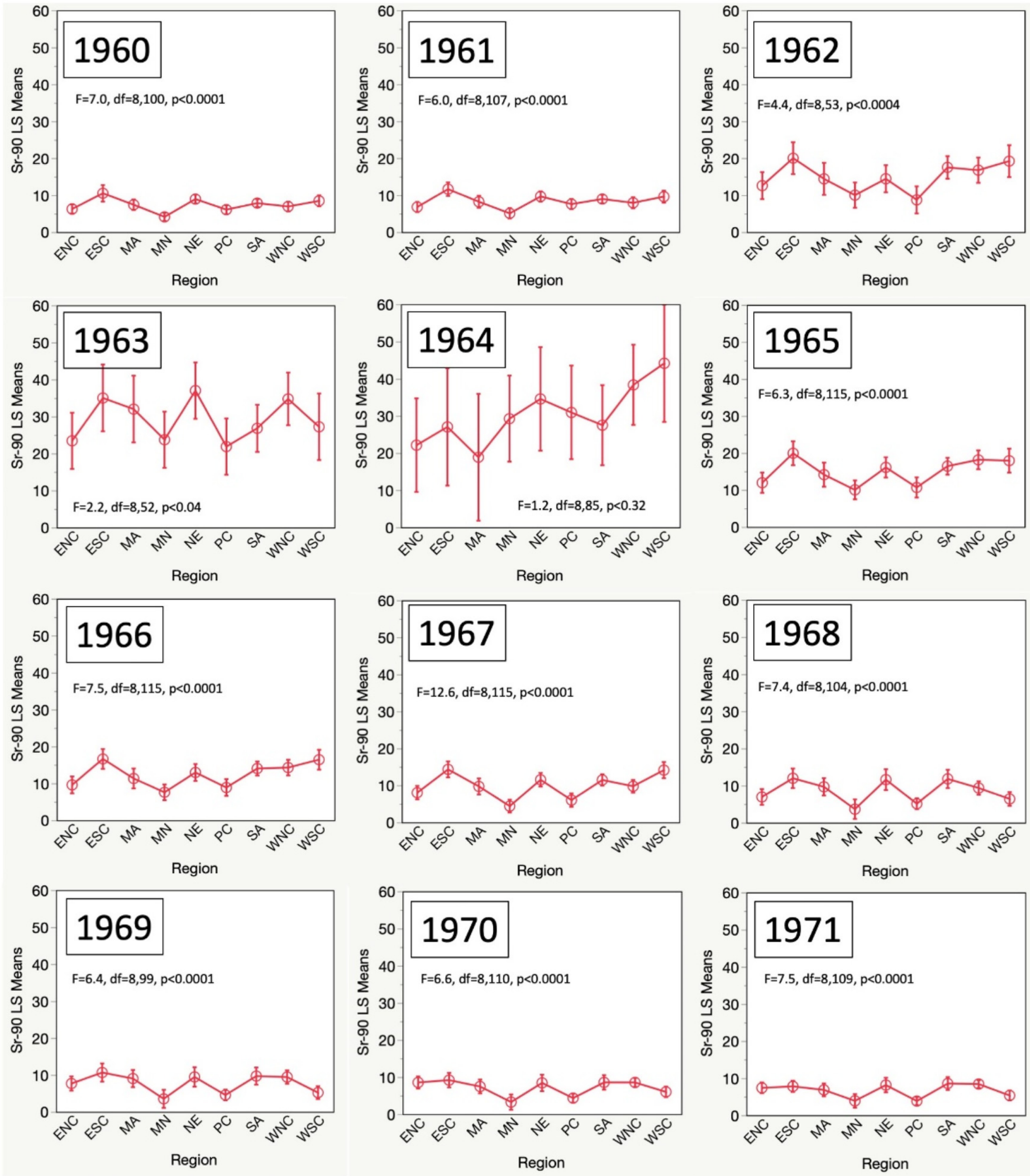


Figure 4. Variation in Strontium-90 (Sr-90) (pCi/l) in milk collected in nine geographic regions from 1960 to 1971. The highest levels were found in 1963 and 1964 in all regions. Least squares means ($\pm$ 1SE) for each location and year of measurement are plotted. ANOVA for each year reported on each panel and indicate highly significant differences among regions for all years ($p < 0.001$) except for 1963 ($p = 0.043$) and 1964 ($p = 0.0.31$) when variances among cities within regions was high. Plots for 1972–1973 not shown, maintain similar decline in Sr-90 as 1970–1971.
Source: U.S. Public Health Service.[57–59].

Discussion

Radioactive fallout from large-scale atmospheric nuclear weapons testing from the early 1950s to the mid-1960s was distributed throughout the world through wind and precipitation and entered human bodies. *In vivo* concentrations reached a peak in 1963 and 1964, as the Limited Test Ban Treaty ended most above-ground tests. Fallout in the milk supply also followed this temporal pattern. In addition, fallout in the Arizona, California, and New Mexico milk supplies was considerably lower than in other areas of the United States.

Data on dietary and *in vivo* levels of Sr-90 in fallout are available. In the United States, government measurements

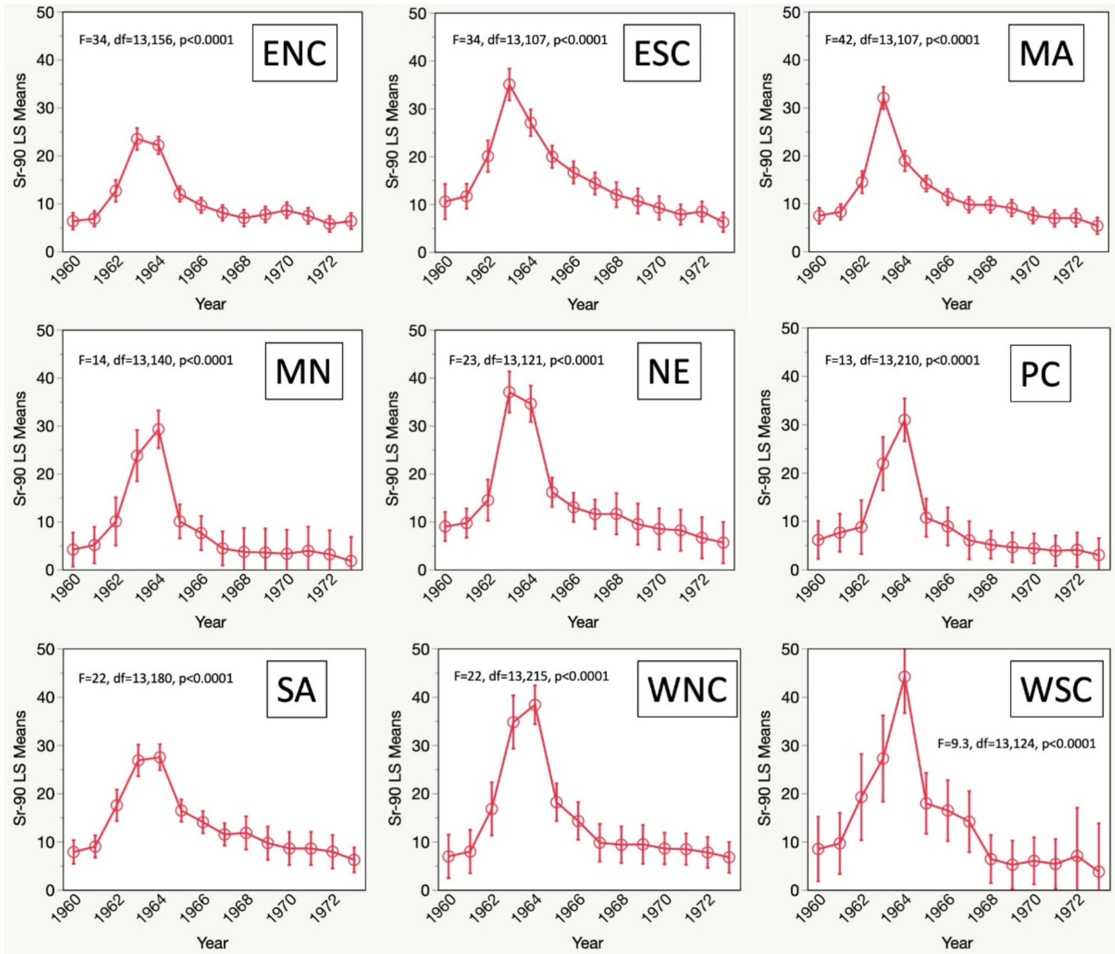


Figure 5. Variation in Strontium-90 (Sr-90) (pCi/l) in milk collected in nine geographic regions from 1960 to 1973 showing temporal changes within regions. The highest levels were found in 1963 and 1964 for all regions. Least squares means (± 1SE) for each year at each location are plotted. ANOVA for year within regions are reported in each panel and indicate highly significant differences among years ($p < 0.0001$) for all regions.
Source: U.S. Public Health Service.[57–59].

of milk and an independent program of measurements in deciduous teeth provided substantial data for temporal trends and spatial patterns of Sr-90.

Health risk posed by exposures to Sr-90 and other forms of radioactivity in bomb test fallout has received little consideration since large-scale testing ended nearly six decades ago. The pattern of rising Sr-90 levels until the early 1960s and the elevated deposition levels in various parts of the United States—compared with relatively modest concentrations in Arizona, California, and New Mexico—identify an opportunity to assess whether these elevated early-life exposures were followed by elevated cancer mortality later in life.

In recent years (2019–2020), all-cancer mortality ratios were consistently lower in the low-fallout area and highest among those born in the early 1960s, when fallout levels peaked. Patterns were consistent for all races combined, plus white non-Hispanics and black non-Hispanics, who were most likely to have been born in the United States than other racial/ethnic groups, mostly Hispanics and Asians.

The knowledge that exposures to radioactivity early in life are more toxic has long been recognized, first with the discovery that exposure to one or more pelvic X-rays *in utero* nearly doubled the risk of the child dying of cancer by age 10[62, 63] and upheld in later analyses.[41–43] This knowledge supports exploration of whether subsequent cancer patterns were affected by exposure to bomb test fallout. Various estimates of increased risk early in life have been made; for example, an analysis of twenty-seven studies of rodents covering eighteen chemicals concluded that early life exposures posed a ten times greater cancer risk than adult exposures.[56]

Fallout exposed Americans to relatively low doses of radioactivity, compared to some other irradiated populations. However, the linear no-threshold dose-response relationship between radiation exposure and health risk has established that low-dose exposures can be harmful.[44]

Table 3. Mortality Rate per 100,000 Population, all Neoplasms, 2019–2020 Deaths by Birth Cohort, by Race, and Ethnicity Three Low-Fallout States versus All Other United States.

Birth years	Age	47 U.S. States + DC Rate (95% CI), Deaths	Three States (AZ, CA, and NM) Rate (95% CI), Deaths	Ratio
White non-Hispanic				
1945–1949	70–74	679.0 (479.3–484.9) 132572	616.4 (606.5–626.2) 15063	1.102*
1950–1954	65–69	482.1 (479.3–484.9) 112620	432.1 (424.4–439.9) 12002	1.116*
1955–1959	60–64	344.3 (342.1–346.5) 91182	295.0 (288.9–301.2) 8950	1.167*
1960–1964	55–59	213.8 (212.0–215.5) 57001	176.7 (171.9–181.4) 5263	1.210*
Black non-Hispanic				
1945–1949	70–74	795.1 (784.0–806.1) 19996	804.0 (7613.1–845.0) 1481	0.989
1950–1954	65–69	618.6 (610.4–626.9) 21630	616.8 (586.2–647.5) 1556	1.003
1955–1959	60–64	434.8 (428.7–440.9) 19465	420.8 (398.8–442.8) 1404	1.033
1960–1964	55–59	266.7 (262.2–271.3) 13141	233.3 (217.8–248.8) 871	1.143*
All races and ethnicities				
1945–1949	70–74	665.4 (662.1–668.6) 164479	575.6 (568.2–583.1) 22933	1.156*
1950–1954	65–69	479.0 (476.5–481.5) 145910	402.3 (396.7–407.9) 19581	1.191*
1955–1959	60–64	339.2 (337.3–341.1) 120906	275.7 (271.4–280.0) 15787	1.230*
1960–1964	55–59	209.0 (207.6–210.5) 78055	167.3 (164.0–170.5) 10274	1.249*

All ratios are statistically significant and is marked with an (*).
Source: Centers for Disease Control and Prevention.[60]

Potential causes of cancer mortality are multiple. Often-cited factors include socioeconomic status, body mass index, smoking, educational levels, exposure to environmental toxins, and others. Assessing cancer mortality in areas of the United States based on one factor—concentrations of Sr-90 in bodies from bomb fallout at birth—poses one limitation to the analysis.

In addition, cancer mortality data in this report are aggregate data based on residence at death, without identifying place of birth. Thus, the inability to account for in- and out-migration from regions poses another limitation to the analysis. The likelihood of increased exposures in the United States to toxic chemicals (other than bomb test fallout) from the late 1940s to the early 1960s, and not knowing if these increases varied by state, also pose a limit to drawing firm conclusions from current mortality.

While exposure to radioactivity increases the risk of all cancers, using mortality of all cancers combined may obscure any potential effect on cancers known to be radiosensitive. For example, exposure to radioactive strontium poses a heightened risk of bone cancer, as this isotope seeks out bone. However, bone cancer is a relatively uncommon cause of death, and low numbers would likely reduce the ability to detect significant patterns. For example, in 2019–2020, only 27 residents of Arizona, California, and New Mexico aged 55–59 died of bone cancer, along with 54 who were aged 70–74.

This report has taken a first, albeit preliminary, attempt to assess any correlation between early-life exposures to nuclear weapons fallout and later-life mortality risk. It is important that this research continues using enhanced methods.

The methodology presented here can be enhanced in subsequent reports. Isotopes other than Sr-90—such as Cesium-137 and Plutonium-239—can be measured in deciduous teeth and used in comparisons with later-life health outcomes. Cancer incidence can be used as a measure of health status, to augment cancer mortality. For radiosensitive cancers with a relatively low mortality, such as thyroid cancer, incidence data is potentially helpful.

Conclusions

No definitive conclusions on the link between exposure to fallout and health risk can yet be drawn from this report. However, elevated mid-life cancer mortality among persons born during atmospheric nuclear weapons testing in areas with relatively high bomb fallout suggests more studies are merited. Comparing the proportion of deciduous tooth donors born in high- versus low-fallout areas who have since died of cancer would enhance the understanding of latent effects of exposures. The existence of 100,000 deciduous teeth from persons born during bomb testing makes this comparison possible.

Furthermore, the collection of baby teeth can potentially serve as basis for a case–control study. Of the 37,000 donors of the 100,000 deciduous teeth, born between fifty-five and seventy-five years ago, an estimated 6,000 are deceased (of which about 1,600 were from cancer). Measurement of Sr-90 levels in deciduous teeth of these decedents—for whom the place of birth is known—and comparing them with Sr-90 in teeth of matched controls born in the same city/state—has commenced.[53] Extending this analysis to larger populations could provide useful information to better understand the health impact of global bomb testing on U.S. residents.

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Appendix

Appendix A. Average Annual Picocuries Strontium-90 (Sr-90) per Liter Pasteurized Milk, 1960–1973 United States, by City (U.S. Average for 60 Sites = 11.23).

City	Average	City	Average
Albuquerque NM	4.43	Memphis TN	14.64
Atlanta GA	15.36	Milwaukee WI	8.43
Austin TX	3.86	Minneapolis MN	15.57
Baltimore MD	12.00	Minot ND	19.14
Boston MA	16.07	Montgomery AL	10.36
Buffalo NY	9.36	New Orleans LA	23.21
Burlington VT	12.86	New York NY	13.68
Charleston SC	15.57	Norfolk VA	14.07
Charleston WV	13.57	Oklahoma City OK	10.64
Charlotte NC	17.57	Omaha NE	10.64
Chattanooga TN	17.39	Palmer AK	9.07
Chicago IL	9.93	Philadelphia PA	10.75
Cincinnati OH	10.93	Phoenix AZ	2.14
Cleveland OH	10.93	Pittsburgh PA	14.61
Denver CO	8.71	Portland ME	14.29
Des Moines IA	10.68	Portland OR	11.64
Detroit MI	9.43	Providence RI	12.93
Grand Rapids MI	10.64	Rapid City SD	15.64
Hartford CT	11.07	Sacramento CA	3.64
Helena MT	10.71	Salt Lake City UT	9.07
Honolulu HI	4.57	San Francisco CA	3.71
Idaho Falls ID	10.21	Seattle WA	12.43
Indianapolis IN	10.29	Spokane WA	11.07
Jackson MS	18.21	St. Louis MO	11.21
Kansas City MO	11.86	Syracuse NY	10.29
Laramie WY	8.43	Tampa FL	7.79
Las Vegas NV	3.07	Trenton NJ	11.21
Little Rock AR	21.71	Washington DC	10.64
Louisville KY	14.71	Wichita KS	10.21
Manchester NH	15.93	Wilmington DE	12.21