

**ELEVATED IN VIVO STRONTIUM-90 FROM
NUCLEAR WEAPONS TEST FALLOUT AMONG
CANCER DECEDENTS: A CASE-CONTROL
STUDY OF DECIDUOUS TEETH**

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Risks to health from large-scale atmospheric nuclear weapons testing are still relatively unknown. A sample of 85,000 deciduous teeth collected from Americans born during the bomb-testing years assessed risk by in vivo measurement of residual strontium-90 (Sr-90) concentrations, using liquid scintillation spectrometry. The authors' analysis included 97 deciduous teeth from persons born between 1959 and 1961 who were diagnosed with cancer, and 194 teeth of matched controls. Average Sr-90 in teeth of persons who died of cancer was significantly greater than for controls (OR = 2.22; $p < 0.04$). This discovery suggests that many thousands have died or will die of cancer due to exposure to fallout, far more than previously believed.

INTRODUCTION

*Bone and Tooth Studies Measure Internal Doses
of Nuclear Weapons Test Fallout*

A total of 422 nuclear weapons were detonated in the atmosphere by the United States (206 tests) and the Soviet Union (216 tests) before large-scale testing ended with the 1963 Partial Test Ban Treaty (1, 2). Yield from the six largest Soviet tests alone totaled 136.9 megatons, or the equivalent of nearly 4,000 Hiroshima and Nagasaki bombs (36 kilotons). As testing escalated, deposition of fallout in human bodies was documented around the world (3). The most

commonly measured isotope in fallout was strontium-90 (Sr-90), taken up in bone and bone-like structures due to its chemical similarity to calcium.

Sr-90, with a physical half-life of 28.7 years, was viewed as a surrogate measure for the internal dose of long-lived (and perhaps all) mixed fission and activation products in fallout. The U.S. government conducted two programs measuring Sr-90 uptake from fallout in human bone. One used adult bones from decedents in New York City, San Francisco, and Chicago, collected from 1954 to 1982 (4). The other used bones of deceased individuals under age 25 from 30 U.S. locations, collected from 1962 to 1971 (5, 6). Both programs documented steady increases of average Sr-90 concentrations in bone during atmospheric nuclear weapons testing, and a marked decline after the Test Ban Treaty went into effect.

Other studies of Sr-90 deposition analyzed shed deciduous teeth, a method first proposed in 1958 (7). Researchers from several nations conducted such analyses, the largest of which occurred in the United States (8, 9). Deciduous teeth were also tested in Denmark (10), Finland (11, 12), Germany (13), Italy (14), and the United Kingdom (15). Like the bone studies, these efforts all showed marked increases in Sr-90 concentrations in deciduous teeth during the nuclear weapons testing period, and substantial declines after testing ended.

Calculations of uptake of radionuclides by measuring Sr-90 in deciduous teeth, employing a methodology similar to the tooth studies of bomb fallout, have also been used for populations living near nuclear reactors. In vivo levels increased in the Ukraine (16) and Greece (17) after the Chernobyl accident, and other analyses documented increased concentrations of isotopes in teeth near reactors in the United Kingdom (18) and the United States (19).

Significant Rises in Childhood Cancer during Period of Bomb Testing

Elevated rates of bone and other cancers were found in animals administered doses of Sr-90, including rats (20), mice (21), rabbits (22), swine (23), and dogs (24). Studies evaluating human carcinogenesis through the use of in vivo measurements of Sr-90 have been almost nonexistent, even in the presence of vital statistics patterns suggesting the potential for such a link.

In particular, elevated risk of childhood cancer has been linked with various sources of irradiation, beginning in the 1950s, with a relatively short latency of 10 years or less between exposure and cancer manifestation. These types of exposures include therapeutic head and neck X-ray irradiation (25–27); in utero exposure to pelvic X-rays (28–30); irradiation from the Chernobyl accident in Belarus and the Ukraine (31–33); and proximity to nuclear power plants (34–36).

The period of atmospheric nuclear weapons testing was marked by significant increases in cancer in young children, who are at greatest risk for carcinogenic effects of exposure to radioisotopes. Connecticut was the only U.S. state with an established tumor registry during the fallout period. In this state, cancer incidence

for the 0–4 age group rose 39.6 percent ($p < 0.000001$) from 1935–50 (before large-scale testing) to 1951–64 (during large-scale testing). Rates declined 18.9 percent ($p < 0.005$) in 1965–69 (37), the first five years after the peak fallout levels (Table 1). By 1969, typical levels of long- and short-lived fallout in the environment and in human bodies had diminished by 50 and 100 percent, respectively. The highest cancer rates in young children occurred in 1962–64, when fallout levels in the environment, diet, and body peaked. Cancer manifestation before age 5 probably represents an insult in utero and/or during infancy.

The first publication suggesting a link between elevated U.S. cancer rates and bomb fallout did not appear until 1967 (38), more than two decades after the first nuclear weapon detonation. Other reports identified elevated rates of various cancers in highly exposed populations in Utah, based on estimated doses from fallout measured in the environment (39–41). No national analysis was conducted until 1999, when 11,300 to 212,000 cases of thyroid cancer in Americans were estimated to be caused by iodine-131 in Nevada bomb test fallout (42). An unreleased 2002 U.S. government progress report estimated that 35,000 cancer cases, 15,000 of which were fatal, were caused by bomb fallout (43).

Lack of Studies Matching In Vivo Radionuclide Levels with Adverse Health Effects

Data documenting in vivo levels of bomb test fallout in the United States have never been used to calculate potential risks to health. The projection of thyroid cancer cases used estimates of iodine-131 uptake from milk samples (44). During the period of atmospheric bomb testing, this matter was raised but went unanswered, even though measurements of Sr-90 concentrations in bone and teeth were being compiled. The work of the U.S. Atomic Energy Commission's William Neuman was cited as the basis for statements such as the following, from 1956: "Bombs may have already propelled enough strontium 90, the most

Table 1

Leukemia and all-cancer incidence, age 0–4 years, Connecticut, United States, before, during, and after atomic bomb testing

Period	Cases	Ann. pop.	Cases per 100,000	Rate change, %
1935–50 (before testing)	296	145,235	12.74	—
1951–64 (during testing)	629	252,740	17.78	+39.6 ($p < 0.000001$)
1965–69 (after testing)	193	267,687	14.42	–18.9 ($p < 0.005$)
Highest rate: 1962–64	171	279,663	20.38	

pernicious aftermath of nuclear fission, into the stratosphere to doom countless of the world's children to inescapable and incurable cancer" (45).

Several case-control studies from the 1960s that compared Sr-90 levels from bones of autopsied persons with and without cancer were inconclusive. One of these reports did not include bones of children (46), while only one-quarter of the samples in the other reports were bones of children (47, 48), even though exposures to the young would be most likely to document risk. For more than four decades, there has been no published research matching *in vivo* fallout with health effects.

The need for study on this topic is heightened by the presence of nuclear power reactors built since the cessation of atmospheric nuclear weapons testing. Reactors produce the same radioisotopes found in bomb test fallout, and routinely release a portion of them into the air and water. These chemicals contaminate humans as they breathe air and ingest food and water. Thus, any studies of health effects of early life exposure to bomb fallout in the 1950s and 1960s are relevant to subsequent generations exposed to reactor emissions as infants and children.

Comparing internal doses from bomb fallout and reactor emissions is a highly complex undertaking. It is clear that radionuclide levels in milk were considerably greater from bomb fallout than from reactor emissions. However, large-scale atmospheric testing only occurred for a period of 12 years, whereas nuclear reactors have operated for more than half a century, raising the possibility that cumulative and continuous doses to the population from the two sources may be roughly comparable. One report links trends of Sr-90 in deciduous teeth of children living near U.S. reactors with trends in local rates of cancer incidence in children age 0–9 years, supporting the need for more detailed study (49).

*Collection of 85,000 Deciduous Teeth
Provides Basis for Study*

From 1958 to 1970, scientists at Washington University in St. Louis, Missouri, collaborated with local citizens to collect shed deciduous teeth for the purpose of making *in vivo* measurements of Sr-90 uptake from fallout. Approximately 320,000 teeth were collected during this time. Beginning with publication of initial results in 1961 (8), the Washington University effort was recognized as the most comprehensive analysis of *in vivo* uptake of bomb fallout in the United States.

This extensive collection of tooth samples was never used for any study of health outcome. However, Washington University officials recently discovered 85,000 of the 320,000 teeth not used in the initial study. Each tooth is secured in an envelope with information attached to a card, identifying the tooth and tooth donor. These 85,000 remaining teeth were donated to the Radiation and Public Health Project research group (50). The teeth provide a basis for assessing any health risks from long-lived radioisotopes taken up from bomb fallout.

Such assessment can also provide the basis for measuring health outcomes in succeeding generations as a result of exposure to reactor emissions.

PRELIMINARY ASSESSMENT OF FEASIBILITY

Ability to Accurately Measure Residual Sr-90 in Teeth

The majority of the 85,000 teeth in the sample were from persons born between 1955 and 1964. As the physical half-life of Sr-90 is 28.7 years, 30 to 50 percent of the original uptake of this radionuclide still exists in tooth enamel. The original study used batches of 20 incisors and 5 molars to obtain accurate results, and thus the current study addressed the ability to accurately measure the remaining Sr-90 in teeth by using batches of 10 teeth each.

Initial measurements were conducted by the Department of Earth and Environmental Sciences at the University of Waterloo in Ontario, Canada, which tested four batches. Each batch was homogeneous with respect to expected Sr-90 level (i.e., molars, 1956 births; incisors, 1956; incisors, 1963; incisors, 1964). Earlier tests showed uptake of Sr-90 to be significantly greater in molars than in incisors, and showed Sr-90 concentrations to peak in 1963–64 (9). All test teeth were from bottle-fed donors, who had higher uptake than breastfed donors (51), and all donors/mothers had lived in St. Louis County during the pregnancy and in the first year of life.

After consistency was established for Sr-90 levels, the University of Waterloo measured Sr-90 with the Perkin-Elmer 1220-003 Quantulus Ultra Low-Level Liquid Scintillation Spectrometer, designed to detect relatively low levels of radioactivity. A second laboratory measured calcium for each batch, allowing calculation of a ratio of picocuries of Sr-90 to grams of calcium. Testing by lab personnel was blinded for date of birth and type of tooth for each batch, to prevent bias in results. Technical methods used to test teeth are described in Appendix I (appendixes begin on p. ____).

Table 2 compares University of Waterloo results of Sr-90 tests for 40 teeth (four batches) with original results from Washington University. Both studies found that Sr-90 was slightly higher in 1964 incisors than in 1963 incisors, much higher in 1963–64 incisors than in 1956 incisors, and moderately higher in 1956 molars than in 1956 incisors. The Waterloo test split one batch (batch 4) into 5 teeth each, and Sr-90 levels were similar. These results show that accurate measurement of Sr-90 from bomb fallout in teeth is feasible using batches of 10 teeth. Sr-90 levels detected by Washington University in the 1960s were (predictably) higher than those found in 2009 by the University of Waterloo, as 50 to 70 percent of the original Sr-90 has decayed. Given that 10 half-lives are needed for Sr-90 to completely decay, nearly 300 years will be required for the isotope to dissipate completely.

Table 2

Sr-90 concentrations, in picocuries of Sr-90 per gram of calcium, for deciduous teeth, persons born 1956, 1963, and 1964, data from University of Waterloo and Washington University School of Dentistry

Batch	Birth year	Type of teeth	U. of Waterloo (no. of teeth)	Washington U.
1	1964	Incisors	6.21 (10)	8.9
2	1963	Incisors	4.73 (10)	6.1
3	1956	Incisors	0.57 (10)	2.0
4	1956	Molars	0.73 (5)	2.7
4	1956	Molars	0.98 (5)	2.7

Ability to Identify Significant Numbers of Tooth Donors with Cancer

The type of information identifying each of the 85,000 teeth and donors is shown in Table 3. All data were originally recorded by volunteer citizens who orally questioned parents of the tooth donors. Data describing each tooth (type, whether carious, whether restored, root/rootless) were recorded by Washington University dentists who inspected the teeth.

Any retrospective study of cancer risk from in vivo uptake of bomb fallout would have to identify tooth donors who have been diagnosed with cancer, a process dependent on the completeness and accuracy of reporting cancer diagnoses and/or deaths among tooth donors. A sample of tooth donors was used to assess the feasibility of accessing such information. Of a sample of 125 male tooth donors, current addresses were found for 80 percent; and 35 percent of mailed surveys were completed and returned. These results indicated that a significant number of self-reported cancers could be collected through mail surveys.

Accessing mortality records is possible through the National Death Index and/or the Missouri Department of Health and Social Services, both of which maintain records of all deaths in the nation and state since 1979. Vital statistics suggest that the majority of deceased tooth donors died in Missouri. About 7 and 3 percent, respectively, of male and female Americans who were children in the 1960s, when most of the 85,000 deciduous teeth in the database were donated, have died, suggesting that a sufficient number of deaths can be identified.

Table 3

Information for each tooth and donor, 85,000 deciduous teeth, United States

Tooth identification number	Tooth type (incisor, cuspid, molar)
Sex	Cariou/noncariou
Birth date	Restored/nonrestored
Year tooth lost	Root/rootless
Mother's residence during pregnancy	Name of child
Child's residence during the first year	Name of parent(s)
Months on breast milk	Address
Months on formula/bottle	Telephone
Kind of milk used in formula	

*Suitability of Using Sr-90 as a Proxy for
Uptake/Risk of Fallout*

Strontium-90 detected in deciduous teeth represents exposures through dietary pathways—that is, through maternal bone stores/maternal diet during pregnancy and milk intake during early infancy. During bomb testing, an estimated 54 percent of the Sr-90 dietary uptake occurred through milk, with the remainder from wheat (20%), vegetables (15%), fruit (8%), meat (2%), and eggs (1%) (28). Historical data show a correlation between Sr-90 patterns in the milk supply and the body (bone/teeth) (9, 52). Thus, Sr-90 in teeth is a useful indicator of uptake of bomb fallout, as a function of diet.

Sensitivity to radiation is elevated from conception through embryonic and fetal development to infancy (53–55). A recent report estimates that, compared with adults, harm is three times greater for children exposed at ages 2–16 years, and ten times greater for those exposed at ages 0–2 years (56). Fetal exposures pose an even greater risk than comparable doses to infants and children. Given that Sr-90 in deciduous teeth represents uptake in the in utero period, this radionuclide is suitable for studying health risks from exposure early in life.

Sr-90 has multiple pathogenic effects in the body. Along with other radioactive strontium isotopes, it is a genotoxic carcinogen. Experiments on animals exposed to radioactive strontium (57, 58) have identified elevated levels of a variety of cancers, including sarcomas, soft tissue cancers, respiratory cancers, leukemia, oral/nasal/periodontal cancers, lymphoma, basal/squamous cell cancers, pituitary adenoma, and tubular adenoma of the ovary. When consumed orally or inhaled, the most serious immediate consequences of Sr-90 exposure are hematological:

reductions in white blood cell count that adversely affect the ability to resist infectious disease. Along with cancer and immune suppression, radioactive strontium has been shown to adversely affect the musculoskeletal, respiratory, cardiovascular, gastrointestinal, ocular, and neurological systems, and to cause chromosomal defects and other reproductive disorders (59). Thus, studying the health effects of nuclear weapons test fallout by measuring Sr-90 concentrations in deciduous teeth can be useful for studying diseases other than cancer.

There are legitimate concerns with reliance on Sr-90 in deciduous teeth for estimating total bomb fallout uptake in humans. Sr-90 is only one of more than 100 radionuclides created in nuclear weapons detonations. Some fission and activation products have relatively short half-lives, measured in minutes, hours, or days, whereas others (including Sr-90) are relatively long-lived. However, historical (geographic and spatial) patterns of Sr-90 in milk are similar to those of other long-lived isotopes such as cesium-137 (52). Thus, although Sr-90 cannot be assumed to be a proxy for short-lived isotopes, it is representative of long-lived ones.

MATERIALS AND METHODS

The case-control study approach in this report identifies batches of teeth that are homogeneous with respect to fallout exposure. Case-control studies documenting elevated cancer rates in irradiated populations include children subjected to in utero pelvic X-rays (60, 61); children after the Chernobyl accident (62, 63); and children of workers at nuclear plants (64, 65). A case-control study of 1,177 leukemia deaths found an association between (estimated) bone marrow dose from Nevada bomb test fallout and leukemia, especially for those in the high-dose group and those under age 20 at exposure (40).

Only male tooth donors are included in the study, as they are easier to identify at current addresses or in death registries. (Men generally do not change their names after marriage.) Study teeth are restricted to incisors (which take up 40% less Sr-90 than molars and cuspids); teeth from children with little or no breastfeeding (who take up about 25% less Sr-90 than bottle-fed children); and teeth from those living in the metropolitan St. Louis area during the pregnancy/first year of life, when Sr-90 was taken up in fetal tooth buds (other geographic areas had different exposures to fallout than St. Louis).

The final criterion for inclusion in the study is a birth date from January 1, 1959, to June 30, 1961. This period was marked by a moratorium on atmospheric nuclear weapons testing by the United States and the Soviet Union, and virtually no short-lived radioisotopes were present in the environment. Hence, any comparison of Sr-90 levels between cases and controls will not be affected by differences in exposures to short-lived fallout. A total of 6,340 deciduous teeth met the study criteria, representing 3,900 tooth donors, as some donors gave more than one tooth.

Matching the name and date of birth recorded at the time of tooth donation in the 1960s with those in current voter registration records in the states of Missouri and Illinois, along with an Internet search of residential listings for donors with rare surnames, provided current addresses for 2,703 (69.3%) of the 3,900 tooth donors. Voter registration records also identified current addresses of 648 parents of tooth donors with no current address, of which 247 (6.3%) were included in the study. The total number of addresses used in the study was 2,950 (75.6% of 3,900).

Early in 2009, health surveys were sent by U.S. mail to the 2,950 tooth donors or parents. The surveys, which explained the original Washington University study and the current study, asked recipients to confirm the accuracy of name, birth date, and parent name, and to confirm any diagnosis of cancer, noncancerous tumors, or polyps, with year of diagnosis and type of cancer. Of the 2,950 surveys, 986 (33.4%) were completed and returned (876 from donors, 110 from parents) (Table 4). Only 53 (1.8%) indicated the survey had been sent to the wrong person; and 108 (3.6%) were returned due to an incorrect address. Responses included 65 tooth donors with tumors, 51 of which were malignant.

Death registrars at the Missouri Department of Health and Social Services were sent a list of the 1,197 tooth donors with no current address. The department attempted to match the donor name and date of birth recorded at the time of tooth donation with those in records of deaths occurring in the state from 1979 to

Table 4

Results of mailed health survey to donors of deciduous teeth
and parents of donors

	From 2,703 surveys to tooth donors		From 247 surveys to donor parents	
	Number	Percent	Number	Percent
No health conditions identified	668	24.7	69	27.9
Cancer	47	1.7	4	1.6
Nonmalignant neoplasms	13	0.5	1	0.4
Other health conditions	111	4.1	16	6.5
Wrong person	33	1.2	20	8.1
Blank forms	4	0.1	0	0.0
Total surveys returned	876	32.4	110	44.5
Returned—incorrect address	101	3.7	7	2.8
No response	1,726	63.9	130	52.6

2007. It found 84 such matches, and provided the decedent name, date of death, and primary cause of death (ICD-9 codes for 1979–98 deaths, ICD-10 codes for 1999–2007 deaths). Of the 84 matched deaths, 12 were due to cancer. Thus, a total of 77 tooth donors with cancer (65 survivors and 12 decedents) were identified from the health surveys and the death records search. A 13th death of a tooth donor was identified by parents in their response to the survey. The average age at death for cancer decedents was 39.9.

The 77 tooth donors with cancer had donated 122 deciduous teeth to the original study that were never tested for Sr-90. Of these, 25 teeth from 9 persons were eliminated, as no control tooth matching the study criteria existed in the database. Thus, 97 teeth from 68 donors formed the cases of the case-control study. Matched controls included those who confirmed the accuracy of name, birth date, and parent name and had never been diagnosed with cancer or other significant health condition. Two teeth from matched controls were selected for each case; the total of 194 controls (97×2) represents 141 donors.

Selection of matched controls used several criteria. The donor birth date for each of the 194 control teeth was less than 40 days different from that for the corresponding case donor. The matched donor lived in the same county as the case donor in utero (during pregnancy) and in the first year of life (181 teeth), or a county immediately adjacent (13 teeth). Teeth from matched donors were marked as incisors or unmarked, similar to those in the original study (162 and 32, respectively). The year the tooth was shed was the same for matched controls as for the corresponding case for 101 teeth, and differed by one year for 60 teeth (the other 33 differed by 2 to 3 years, or unknown). Average months of breastfeeding for case and control teeth were 0.426 and 0.409.

The University of Waterloo received samples blinded to any information about the teeth. All but one of the 10 batches of case teeth had 8 to 12 teeth, and one had 5; control batches always had twice the number of teeth as the corresponding cases. Testing took place during July 2009. After the calcium content had been measured, the lab tested each batch for Sr-90 concentration in 8 separate intervals of 50 minutes. Technical information on testing methods is given in Appendix I.

Calculation of the ratio of Sr-90 to calcium for each batch used a standard formula from previous studies. For the numerator, average counts per minute minus background radiation times a quench factor was multiplied by 1,000. For the denominator, grams of calcium was multiplied by two conversion factors, 3.46 and 3.80. For each batch, a counting error was calculated, plus or minus two standard deviations from the mean, to produce a 95 percent confidence interval (95%CI). A counting error for groups of batches—that is, for cancer deaths, cancer cases, and controls—was also calculated (the square root of the sum of the error for each batch squared, divided by the number of batches).

RESULTS

Strontium-90 concentrations, expressed as ratios of Sr-90 to calcium (Sr-90/Ca), from laboratory testing for each batch of deciduous teeth are presented in Table 5. A total of 24 batches were analyzed, 10 for cases (odd-numbered batches) and 14 for controls (even-numbered). The laboratory split the largest four of the control samples in half to produce a relatively consistent amount of calcium in each batch, which varies by number of teeth, size of teeth, and presence of decay. One control batch produced a calcium level of 65.13 grams, nearly twice the next greatest amount of 33.05 grams. This sample was eliminated from the analysis, as it most likely represents an erroneous count. We used the results of all other batches, as they are relatively consistent. All results for Sr-90/Ca ratios are expressed in picocuries of Sr-90 per gram of calcium, followed by the 95%CI.

The 20 teeth in two batches from donors who died from cancer had Sr-90/Ca of 7.00 (4.66–9.34), weighted by the amount of calcium in each batch. The Sr-90/Ca of 3.16 (2.49–3.83) for the 29 control teeth in two batches produced an odds ratio (OR) of 2.22 for cases versus controls, significant at $p < 0.04$. Only 29 teeth were in the control group, rather than 40, because one batch was eliminated due to erroneous counts (see above).

The 77 teeth in 8 batches of teeth from cancer survivors had a weighted Sr-90/Ca of 3.94 (2.84–5.04), compared with 5.45 (4.42–6.48) for the 154 control teeth in 11 batches (OR = 0.72, not significant).

The Sr-90/Ca of 12.11 (9.08–15.14) for cancer decedents among 1959 births was significantly greater than the 2.74 (1.95–3.53) for the corresponding controls. The Sr-90/Ca for cancer decedents among persons born 1960–61 (4.76; 3.44–6.08) was elevated, but not significantly, over controls (3.42; 2.89–3.95). Among decedents, types of cancer included brain, bladder, colon, connective/soft tissue, esophageal, rectal, and testicular cancers, leukemia, melanoma, and non-Hodgkin's lymphoma. The average age at death for cancer decedents in both 1959 and 1960–61 cohorts was 39.9 years; the average age at initial diagnosis is unknown.

Unusually elevated Sr-90 concentrations were found in three control batches (Sr-90/Ca of 8.87, 8.81, and 12.08), much greater than in all 8 batches from cancer survivors and all other 11 corresponding control batches. Of the 77 teeth from cancer survivors, 50 were from those with nonmalignant tumors, pre-cancerous polyps, and skin cancers (melanoma, basal cell carcinoma, and squamous cell carcinoma).

Average Sr-90/Ca in the 20 teeth of cancer decedents (7.00, 4.66–9.34) was greater than that in the 27 teeth from cancer survivors with malignant tumors other than skin cancer (4.16; 3.00–5.32), and the 50 teeth from survivors of skin cancers and pre-cancerous tumors and polyps (3.82; 2.83–4.81). Because these ranges overlap, the difference in Sr-90/Ca for cancer decedents and cancer survivors falls short of achieving statistical significance.

Table 5
 Sr-90 concentrations, as picocuries of strontium-90 per gram of calcium,
 in deciduous teeth, cases vs. controls, incisors from St. Louis Area
 bottle-fed males born January 1959–June 1961

Batch/description	Calcium, g	Sr-90/Ca	95%CI
<i>Cases</i>			
1 Cancer deaths 1959	5.43	12.11	9.08–15.14
3 Cancer deaths 1960–61	12.38	4.76	3.44–6.08
5 Cancer survivors 1959	31.89	3.53	2.98–4.08
7 Cancer survivors 1960–61	8.43	5.97	4.06–7.88
9 Cancer survivors 1959	18.70	4.05	3.16–4.94
11 Cancer survivors 1959	25.81	3.12	2.47–3.77
13 Cancer survivors 1960–61	12.97	4.16	2.91–5.41
15 Cancer survivors 1959	14.01	6.32	5.11–7.53
17 Cancer survivors 1959	21.06	2.85	2.08–3.62
19 Cancer survivors 1960–61	17.55	4.01	3.07–4.95
<i>Controls</i>			
2 Controls for batch 1	20.45	2.74	1.95–3.53
2 Controls for batch 1 ^a	65.13	0.50	0.26–0.74
4 Controls for batch 3	33.05	3.42	2.89–3.95

6 Controls for batch 5	20.99	4.24	3.43–5.05	
6 Controls for batch 5	13.22	4.66	3.42–5.90	
8 Controls for batch 7	13.75	4.67	3.48–5.86	
10 Controls for batch 9	16.45	8.87	7.77–9.97	
10 Controls for batch 9	22.61	1.36	0.67–2.05	
12 Controls for batch 11	23.15	5.29	4.53–6.05	
12 Controls for batch 11	21.47	4.33	3.54–5.12	
14 Controls for batch 13	18.43	8.81	7.81–9.81	
16 Controls for batch 15	12.73	12.08	10.64–3.52	
18 Controls for batch 17	17.86	5.03	4.08–5.98	
20 Controls for batch 19	15.34	3.61	2.55–3.67	
Category	No. of teeth	Sr-90/Ca	95%CI	OR
Cancer deaths, batches 1 + 3	20	7.00	6.26–7.74	2.22 ($p < 0.04$)
Controls, batches 2 + 4	29	3.16	2.98–3.34	
Cancer survivors (odd no. batches 7–19)	77	3.94	3.59–4.29	0.72 (NS)
Controls (even-no. batches 6–20)	154	5.45	5.18–5.73	
Cancer deaths	20	7.00	6.26–7.74	
Cancer survivors, malignancies	27	4.16	3.84–4.48	
Cancer survivors, other	50	3.82	3.45–4.19	

^aOne of split samples for batch 2 was not used in analysis, as calcium level of 65.13 was far different than any other sample and not likely to be reliable.

DISCUSSION

Significance of Elevated Sr-90 in the Teeth of Cancer Decedents

This report addresses the health risks from exposure to radioisotopes from atmospheric nuclear weapons tests. The existence of a sample of 85,000 deciduous teeth of Americans born during the years of greatest bomb test fallout (i.e., those receiving in utero exposures); the fact that nearly five decades have elapsed since these exposures occurred; and the ability to measure residual levels of in vivo radioisotopes from bomb tests—all provide a unique opportunity to conduct a retrospective study of the carcinogenicity of fallout.

We measured in vivo radioactive Sr-90 from fallout for 97 cases and 194 controls of donors of shed deciduous teeth. Laboratory tests documented a significantly elevated Sr-90 concentration (OR = 2.22; $p < 0.04$) among those who died of cancer by age 50, but an insignificantly lower concentration for cancer survivors (OR = 0.72; NS). Among survivors, average Sr-90 concentration for those with skin cancers or precancerous tumors or polyps was lower than for those with other malignancies.

The finding of elevated Sr-90 in subjects with fatal cancers supports the concept that in vivo radioactivity in fallout poses a risk for cancer, especially to those with the greatest exposure. The ages at death for decedents were age 25–29, two decedents; age 30–34, two; age 35–39, two; age 40–44, five; and age 45–49, two. The origin of these malignancies is likely to have occurred much earlier than the age at death.

Among the tooth donors with fatal cancers, decedents suffered from brain, bladder, colon, connective/soft tissue, esophageal, rectal, and testicular cancers, leukemia, melanoma, and non-Hodgkin's lymphoma. The risk for each of these is known to be raised by exposure to ionizing radiation, and in the United States each is a compensable condition under a 2000 act of Congress addressed to workers in nuclear facilities (66).

The Sr-90 concentration in teeth of cancer survivors did not exceed that measured in healthy controls. Fifty of the 77 teeth of cancer survivors are from persons with precancerous tumors or polyps or skin cancers, the origins of which may or may not be as sensitive to radiation exposure as cancers such as leukemia and thyroid cancer. The ages at initial diagnosis for cancer survivors were 10–19, three survivors; age 20–29, two; age 30–39, nine; and age 40–49, 35 survivors, 23 of whom were 45–49. A long latency makes it more likely that factors other than in utero radiation exposures affected cancer risk. Nonfatal cancers were self-reported through health surveys, and thus the accuracy of diagnosis may not be as great as that for cancer decedents, identified from official Missouri death records.

Eventually, estimates of cancers from bomb test fallout—testing the accuracy of the U.S. government estimate of 15,000 deaths (44)—could be made using the sample of 85,000 deciduous teeth. Sr-90 can be used as a proxy measure for all long-lived radioisotopes. Uptake in milk measured in tooth donors in the St. Louis area roughly equals the U.S. average (52, 67) (see Appendix II); and uptake for 1959–61 births approximates the average for the birth cohort 1950–69 (see Appendix III). The study would suggest that of the 79.4 million Americans born in the 1950s and 1960s, there is a potential that considerably more will die from cancer resulting from fallout exposure than the previous estimate of 15,000 (see Appendix IV).

*Findings Consistent with Studies Detecting Harm
from Low-Dose Radiation Exposures*

In the past two decades, several reports have challenged the assumption that radiation exposure below a certain threshold dose poses no health risks. Authors of these reports include the American National Academy of Sciences (68). A committee of European experts challenged the current internal radiation dose model used by the International Commission on Radiation Protection, and suggested that it should reduce permissible annual exposure limits from 100 to 0.1 millisieverts (mSv), based on recent findings in biology, genetics, and cancer research (69). In addition to challenging the no-threshold hypothesis, recent reports suggest that calculated doses from internal sources of radiation exposure may have been underestimated 10- to 100-fold (70, 71).

Recently published epidemiological evidence lends credence to the hypothesis that low-dose radiation exposure poses a health risk, especially in utero. These studies include an OR of 1.24 for stillbirths following prenatal external ionizing radiation at 100 mSv (72); progressively lower high school attendance after therapeutic irradiation for cutaneous hemangioma, at ages below 18 months, as low as 20 mSv (73); and an OR of 2.27 for underweight births of babies exposed in utero to dental radiography to the mother of more than 0.4 mSv (74).

To complement these reports, the U.S. Centers for Disease Control and Prevention acknowledged the carcinogenicity of low-dose in utero radiation exposures. The CDC estimated that a prenatal radiation dose of 50 mSv would increase the risk of childhood cancer incidence from 0.3 to 1.0 percent, and lifetime cancer risk from 38 to 40 percent (75). An incremental 2 percent lifetime risk of cancer would mean 1.5 million additional cancer cases when applied to the 75 million Americans born in the period 1950–69. Although precise dose rates cannot be calculated, findings of elevated in vivo Sr-90 in the cancer decedents in our study are likely to be linked with thousands of cancer deaths.

Future Research Based on Findings

Estimates of in vivo radiation health effects from atomic bomb test fallout can be refined. Other birth cohorts can be studied, and surveys conducted to explore confounding factors such as lifestyle, genetics, and other chemical exposures. Searching national death records (not just Missouri records) and including female tooth donors would also strengthen results. Measuring other isotopes is feasible and could be used to test a recent report concluding that plutonium-239/240 is not taken up in utero, based on the theory that it does not cross the placental barrier (76).

*Policy Implications of Research on Atomic Bomb
Fallout in Deciduous Teeth*

Strontium-90 in the deciduous teeth of humans born half a century ago represents fallout from atmospheric nuclear weapons tests, which were moved to underground locations following the Partial Test Ban Treaty passed in 1963, drastically reducing in vivo exposures. However, understanding health risk from exposure to bomb fallout is relevant to understanding current exposures from nuclear power reactors. Currently, 104 reactors are operating in the United States, and 439 worldwide. These reactors create the same fission products as those released by atomic bomb tests, and after these are released from reactors, humans are exposed to the isotopes in the air and in the food chain.

Current radioisotope levels in U.S. food are lower than during the period of atmospheric bomb tests. For example, Sr-90 in pasteurized milk fluctuated between 0 and 10 picocuries (pCi) per liter during the 1950s, reached a high of 25 pCi/L in the spring of 1964, and declined rapidly thereafter. The average U.S. level in the period 2000–2005 was about 0.8 pCi/L, probably representing releases from current sources, chiefly reactors (77). Large-scale bomb tests were conducted for only a 12-year period (1951–63), whereas U.S. nuclear power reactors have been operating since 1957. Extended exposures from reactor emissions may, in time, compare with exposures from bomb test fallout.

Various public decisions are being made to extend reactor licenses from 40 to 60 years; as of early 2010, government officials have granted extensions for 59 of the 104 U.S. reactors, with more being considered. In addition, 33 new reactors have been proposed; early in 2010, the Obama administration pledged to seek legislation to grant government-backed loan guarantees for \$54.5 billion for new reactor construction. Understanding the true risks of humans' low-dose exposures to fission and activation products is critical in determining the health implications of these public policies.

APPENDIX I

Procedures to Measure Ratio of Strontium-90 to
Calcium (Tooth Samples >0.5 g)

- Weigh teeth in a 20 mL scintillation vial. Add enough 2.5% sodium hypochlorite (bleach) solution to cover the teeth and leave for 24 hours at room temperature. Decant the solution and rinse the teeth with deionized (DI) water. Examine the teeth for discoloration and fillings. If color is present, rewash with sodium hypochlorite. If fillings are present, break up the teeth and remove any metal bits.
- Add 30% nitric acid to teeth in few-drop amounts and heat at 80°C until teeth dissolve. Increase heat and boil off the water and acid until sediment is dry.
- Re-acidify with just enough 10% nitric acid to dissolve the precipitate (heat at 80°C). For large samples (>0.5 g), transfer solution to a 250 mL Erlenmeyer flask. Add sodium carbonate very slowly until Ca + Sr precipitates. Wash precipitate with sodium carbonate water (pH < 8) until the solution contains a white precipitate in a clear, colorless solution.
- Dissolve solution in 10 mL of 10% nitric acid. Pipette 0.2 g into a 20 mL glass vial, add 0.6 g of nitric acid, and dilute to 10 g. Send this solution to analytical lab for calcium analysis.
- Pipette 3.8 mL of solution into a plastic scintillation vial, add 18.2 mL of Ultima Gold LLT (Perkin Elmer). Place samples in the counter with background and standard, and count for 8 × 50-minute intervals (total 400 minutes).
- Calculate the Sr-90/Ca ratio:

$$\text{pCi Sr-90/g Ca} = (\text{counts per minute} - \text{background} \times 1,000) / (3.46 \times 3.8 \times \text{g Ca})$$

APPENDIX II

Strontium-90 Concentration in Various U.S. and Canadian
Locations, Incisor Teeth from 1957 Births, Bottle-Fed

Location	Sr-90 concentration
Toronto	1.96
Michigan	2.47
Indianapolis and Chicago	2.77
St. Louis	2.79
East Texas and New Orleans	3.43
California	1.53
Average all locations, excluding St. Louis	2.43

Source: Baby Tooth Survey, Greater St. Louis Citizens' Committee for Nuclear Information (67).

APPENDIX III

Live Births by Year, and Strontium-90 Uptake in Incisors, United States, 1950–69

Year	Live births, thousands	Sr-90 in incisors	Live	Live births, thousands	Sr-90 in incisors
1950	3,632	0.20	1961	4,268	4.81
1951	3,820	0.30	1962	4,167	8.85
1952	3,913	0.36	1963	4,098	10.62
1953	3,965	0.54	1964	4,027	11.80
1954	4,078	1.04	1965	3,760	10.62 ^a
1955	4,104	2.21	1966	3,606	9.44 ^a
1956	4,218	2.26	1967	3,521	8.26 ^a
1957	4,308	2.56	1968	3,501	7.08 ^a
1958	4,255	5.90	1969	3,600	5.90 ^a
1959	4,295	8.26	Total	79,394	—
1960	4,258	4.81			

Sources: Births: National Center for Health Statistics. Sr-90 in incisor crowns: H. L. Rosenthal, Strontium 90 in children, in *Scientist and Citizen*, Greater St. Louis Committee for Nuclear Information, September–October 1964.

^aProjected Sr-90, based on 50% reduction of Sr-90 in St. Louis fetal jaw bones from 1964 to 1969.

APPENDIX IV

Cancer Mortality Rates, United States, Persons Born 1955–64, by Age at Death

Year of death	Age at death	U.S. cancer deaths/100,000	Est. cancer deaths, 1950–69 births ^a
1979–1983	20–24	6.0	22,500
1984–1988	25–29	9.1	34,125
1989–1993	30–34	15.8	59,250
1994–1998	35–39	27.4	102,750
1999–2003	40–44	47.7	178,875
2004–2008	45–49	87.6	328,500
Total cancer deaths age 20–49			726,000
Total cancer deaths age 0–19			75,000
Total cancer deaths by age 50			801,000

Source: National Cancer Institute Surveillance, Epidemiology, and End Results, Cancer Statistics Review, various years (www.seer.cancer.gov).

Note: For age 0–19, an annual death rate of 5/100,000 for 20 years \times 75,000,000 produces the figure of 75,000 deaths. For age 45–49, the years 2002–2006 (most recent) are used for 2004–2008 estimates.

^aDeath rates for 1955–64 births projected to 1950–69 birth cohort using average population of 75 million.

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