Re-Analysis of "Plutonium in Autopsy Tissue": A Case/Control Examination of Nuclear Weapons Sites and Civilian Lung Burden

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Abstract

This research uses advanced statistical techniques to re-analyse the plutonium burden in lung tissue data from "Plutonium in Autopsy Tissue: A Revision and Updating of Data Reported in LA-4875" by McInroy et al. (1979).[1] The use of a general linear model has produced new preliminary findings whose potential was not apparent in the findings of the earlier work. Regions surveyed included Los Alamos National Laboratory (NM), Nevada Test Site (NV), Rocky Flats Plant (CO), and Savannah River Site (SC). This model specified a gamma distribution and linked an exponential function to the dependent variable, plutonium burden in lung, controlling for age, gender, year at death, and location near or downwind from a nuclear weapons facility (or not). Communities downwind of all nuclear weapons facilities showed a significantly higher plutonium lung burden than control communities.

When aggregated, communities close to or downwind from nuclear weapons facilities (cases) experienced potentially as much as 5.8 times the average plutonium lung burden as communities distant from those facilities (controls), all other variables being controlled for. Cases outnumbered controls by 468 to 212, a factor of 2.2. Women showed a 38% higher overall plutonium lung burden than men across the study span of 1959 to 1976, but this could be partly due to the smaller proportion of women in the study, and the fact that case group membership and pre-test ban death years dominate the female subgroup to a greater extent than the male. Both the 5.8 case/control differential and the 38% differential are highly significant at <0.0001 and 0.0018, respectively. Due to gaps in the data, the absolute values of these factors are less precise than desired, but their high probabilities indicate that the true differences between the case/control and male/female subgroups are extremely unlikely to be insignificant. Although communities distant from weapons facilities bore distinctly lower impacts from airborne plutonium exposure, all Americans were at risk for inhaling plutonium. Compared with communities close to weapons testing field laboratories, communities close to weapons manufacturing facilities experienced at least as great a risk of exposure to airborne plutonium. After 1967, the beneficial effect of the Limited Nuclear Test Ban Treaty is visible in the lung statistics, as the yearly coefficients fall from high double digits to the low single digits, and remain there through 1976.

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Of 901 subjects, 680 lung samples were used in this analysis. Of those, 199 samples (100 cases, 99 controls) failed to produce counts detectable by the alpha spectrometry equipment of the time. The true values of these observations fell between 0.00 and 0.017 decays/min, and were recoded to 0.0035. The data, originally published as hardcopy in the McInroy, et al. (1979)[1] article, is now available for free download online at http://carolinapeace.org/content/view/250/73/ at links on the web page, in SAS, SPSS and MS EXCEL formats. For optimum use of the dataset, please download the codebook and read it carefully. It is located at http://carolinapeace.org/content/blogcategory/40/73/.

Introduction

Between 1959 and 1976, the U.S. Atomic Energy Commission supported a human health study located at Los Alamos National Laboratory to study levels of plutonium in occupationally exposed workers and the general public[1]. They were initially concerned with the residents of Los Alamos, New Mexico and the environs, but, after requests from public health officials working in other states,[2] they recruited pathologists at locations around the United States to supply radiosensitive organs and tissues of recently deceased subjects. Over time, 901 subjects were acquired and separated into seven distinct regions, organized into tables: Los Alamos proper (1959-1976), New Mexico and other areas (1959-1976), Colorado (1970-76), New York City (1968), Pennsylvania (1974-76), Georgia and South Carolina (1972-76), and Illinois (1973-76)[1]; also see map.

Samples were radioassayed for plutonium burden by alpha spectrometry and entered into a database. The article describing the data and project, "Plutonium in Autopsy Tissue: A Revision and Updating of Data Reported in LA-4875" by McInroy et al.[1], was published in the journal Health Physics in July 1979. Numerous research projects on the radiobiology of plutonium utilized the data in subsequent years. The summary of results did not find evidence that any area was experiencing organ contamination in excess of other study areas. However, the levels of internal contamination it documented served as an argument supporting the position that atmospheric testing of nuclear weapons was not safe, as it clearly delineated decreasing body burdens of plutonium following the Limited Nuclear Test Ban Treaty (LNTBT) of 1963. The database has been used in publications to the peer-reviewed press by AEC/DOE scientists, mostly on topics of radiobiology, but it has not been available to the general public in digital form until now. Its potential as a tool for regional-scale or national-scale population dose estimation not yet been explored, with one noteworthy exception.

Dr. Joseph J. Shonka of Shonka Research Associates, Atlanta, Georgia, and his research team under contract with the U.S. Department of Energy, have conducted the Los Alamos Historical Document Retrieval and Assessment Project in affiliation with ChemRisk and the US Centers for Disease Control and Prevention.[3] The Shonka research team used the City of Los Alamos table (Table A-1) in the plutonium autopsy database, together with local newspapers, old maps, telephone books and cemetery records, to identify the home addresses of all but about 20 of the subjects. They geocoded these addresses and used tissue contamination data to estimate population dose and enhance dose reconstruction efforts for Los Alamos National Laboratory emissions.[4] Their success with City of Los Alamos data demonstrates the potential usefulness of this database for dose estimation in other regions covered by the autopsy survey.

This article reports results obtained by re-analyzing the plutonium burden in lung tissue data from the autopsy database with a General Linear Model technique. Controls for age, gender, year at death, and location near or downwind from a nuclear weapons facility (or not) were included among

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the model's independent (effect) variables. The use of this model has produced new preliminary findings whose potential was not apparent in the findings of the earlier work. Regions surveyed included four AEC/DOE installations: two testing grounds and two manufacturing facilities: Los Alamos National Laboratory (LANL), used mainly for above-ground testing; Nevada Test Site (NTS), used for both atmospheric testing and underground testing after the LNTBT went into effect; Rocky Flats Plant (RFP) in Denver, Colorado and Savannah River Site (SRS) in Aiken, South Carolina, both nuclear weapons factories processing large amounts of plutonium. The populations centered around Pennsylvania, New York and Illinois were sampled for comparison purposes.

Background

Tests for Geographic Differences

In tests for geographic differences, the Plutonium in Autopsy Tissue team used non-parametric rank tests to seek significant differences of means among six of the seven regional tables. The New York table was excluded because the mean age of its subjects was much lower (younger) than that of the other tables, due to their causes of death having been dominated by violence or trauma. The initial Kruskal-Wallis rank test indicated that a significant difference among lung means existed, so the investigators went to a Mann-Whitney ranked pairwise comparison to identify the location of the difference. Table 1 depicts the results of this comparison, reproduced from Fox, Tietjen and McInroy (1980)'s Table 20, page 890.[10] Regional means are given in parentheses. Each underscore indicates a group of regions within which no significant pairwise means difference was found. The comparison was made using years of death 1974-1975.

Table 1. Mann-Whitney Ranked Pairwise Comparisons
Plutonium Lung Burden, McInroy et al.[1] Regions

Tissue						
Lung	NM(.535)	LA(.447)	GA(.316)	CO(.301)	PA(.271)	IL(.104)

Means are ranked in descending order from left to right. Among the first group (New Mexico, Los Alamos, Georgia-South Carolina and Colorado), no significant difference among any pairwise comparison of those means was found. When considering the group Georgia-South Carolina, Colorado and Pennsylvania, no significant difference was detected. Only the Illinois table, with the lowest mean, was found to be significantly lower than any previous mean, although the magnitude of its difference was not considered important.[1, 10]

Bomb Testing Fallout

Over 500 atmospheric weapons tests were conducted between 1945 and 1980, by the United States and several other countries including the Soviet Union, China, France and the United Kingdom. The U.S., U.K. and Soviet Union observed the Limited Nuclear Test Ban Treaty signed in 1963, and ceased testing nuclear weapons in the atmosphere. France continued testing until 1974; China tested until 1980.[13]

Plutonium isotopes are released by both low- and high-yield weapons. Low-yield fission devices use the radioactive metal as a fuel; the explosion of high-yield (thermonuclear and boosted fission) devices actually produces new quantities of plutonium by activation of ^{238}Uranium and through fusion reactions.[13] The fission process produces most of the important radionuclides in nuclear fallout.[15] The amount of fallout from nuclear weapons tests, its distance and direction traveled, and the length of time it remains suspended in the atmosphere, are a function of the fission yield in megatons (MT) of the device detonated, wind speeds and directions working on the radioactive plume, the location and elevation of the test site, the presence or absence of precipitation intercepting the plume during its traverse, and the fractionation of volatile compounds from refractory compounds within the fireball.

Yield, test platform elevation, location and time of year determine whether the fireball will carry plutonium particles as high as the stratosphere, or remain confined in the troposphere.[15] The tropopause, the boundary between the stratosphere and the troposphere, lies between about 5 miles (7-8 km) above the poles to roughly 10 miles (16-17 km) high at mid-latitudes in summer.[14,15]

Of the 440 MT total yield of all atmospheric tests, about 40%, or 189 MT, was fission yield. Subtracting small fission tests which resulted in local (boundary-layer) fallout, 161 MT (85%) of that total injected fallout into the atmosphere. 145.3 MT' worth of that amount (90%) was propelled into the stratosphere. Of that stratospheric portion, about half reached the upper stratosphere.[15] Fallout from the troposphere, termed "intermediate", is capable of traveling several thousand miles. Global fallout is injected into the stratosphere and circles the globe.

The height to which plutonium is propelled, in addition to the power of the blast and season of the year, determines how small the particle sizes are, how far they will travel, how long they will take to descend to the tropopause, mix with the troposphere, and eventually enter the boundary layer or peplosphere, that membrane of atmosphere closest to the earth's surface where particulate plutonium interacts with plants, animals and populations. The residence half-time of particles descending from above the stratosphere (~4% of the 161 MT total) is 3.4 years, and just above and just below one year for upper and lower stratospheric deposits. 87% of upper-stratospherically deposited fallout will have descended to the tropopause by around the end of three years post-explosion. There, plutonium has been observed to remain airborne between 44 and 96 days, with a mean of 71 days.[16] Taken together, by the end of four years, up to 90% of a large test's yield released at from an elevated platform will have descended to the boundary layer.

Plutonium in the Environment

Time taken to descend from the atmosphere is not the only time period to consider when asking, "How long will this plutonium deposit be available for inhalation?" Plutonium particulates display two characteristics, hygroscopicity and resuspendibility, which prolong their residence time in the boundary layer. Hygroscopicity, the tendency of a substance to repel water, inhibits plutonium-bearing particles from forming rain droplet nuclei. More soluble fallout constituents such as Strontium-90 are scrubbed from the atmosphere by rainfall. In contrast, airborne plutonium resists such scrubbing action. Magno, Kauffman and Shleien observed that there was "[n]o discernible pattern of concentration or deposition with rainfall" through the period of May 1965 to April 1966 in Winchester, Massachusetts. Instead, the monthly soil-deposited concentrations of plutonium varied from 0.86 to 8.8 pCi/m^2 (3.182 – 32.56 cbq), in agreement with measurements taken elsewhere in the U.S. and Canada and reported in 1958, 1960 and 1963.[17] When rain washed out ^{90}Sr, the ratio of soil-deposited ^{90}Sr/^{239}Pu was as high as three times the ^{90}Sr/^{239}Pu concentration ratio in ambient air in this study. This hygroscopic behavior also prevents soil-deposited plutonium from migrating any deeper into the soil column than 2-3 cm. Most soil-deposited plutonium remains on the surface, exposed to the boundary layer.

Resuspendibility, the capacity of plutonium-bearing particles to detach from the medium on which they are deposited and become airborne again, causes fallout plutonium to become available for inhalation every time the soil is disturbed by plowing, mowing, vehicle wheels, construction activities, etc. Plutonium adsorbed onto blades of grass, tree leaves and other movable objects also resuspends when wind and vibration cause these items to flex or shake.[18, 19]

Fallout plutonium originating in the stratosphere has displayed an average particle size of roughly 0.4 micron.[17] Soil-deposited plutonium from Savannah River Site's chemical separations facilities averaged 1.20 microns in sampling year 9/75 to 9/76, and 0.46 micron in the year 9/76 to 9/77.[20] Particles less than 5 microns can be inhaled and retained in the human lung;[21] submicron particles have the highest retention rates and are responsible for the highest lifetime dose commitments.[17, 19, 21]

Hygroscopicity and resuspendibility make plutonium-bearing particles continually available for inhalation for many years after they have been deposited from the atmosphere. Beck and Bennett observed in 2002, "The impact of weapons fallout will continue to be felt for years to come since a contaminant baseline has been imposed on the ambient radiation environment that will be an important factor in the assessment of past and future releases of radioactive materials into the biosphere."[13]

Methodology

Data Entry

Data entry workers double-entered the data from magnified copies of the data tables in the original McInroy et. al. (1979)[1] article. After entry, both versions were reconciled using comparison procedures. This digital version is now available for free download online at http://carolinapeace.org/content/view/250/73/ at links at the bottom of the webpage, in SAS, SPSS and MS EXCEL formats. The codebook for optimum use of the dataset is located at http://carolinapeace.org/content/blogcategory/40/73/.

Model Selection

To generate the results in this article, a general linear model is used with a link to a logarithmic function, to accommodate the ratio character of the dependent variable (plutonium burden expressed in decays per minute per kg standard organ (dpm/kg, `LUNG_ACTSTDORG`). PROC GENMOD from SAS[5] was selected because it has a log function link and permits the user to specify a variety of distributions. Here, a gamma distribution is selected. The resulting coefficient estimates are then exponentiated to scale them back to more meaningful numbers. The probability distribution is chi-square. The independent variable `YEAR_DEATH` is recoded into individual years (`Y59-Y63` and `Y66-Y76`) to examine time trend in plutonium lung burden. `TESTBAN` is a dichotomous variable dividing observations into two periods: 1959-1963 (pre-testban) and 1966-1976 (post-testban), based on `YEAR_DEATH`. `GENDER`, `AGE`, and `YEARS_RESIDE` are used as independent variables, available in the database case records. Environmental Systems Research Institute (ESRI)'s ArcGIS software[6] derived distances between the subjects' `CITY_OF_RESIDENCE` and the four weapons sites. An inverse exponential function of distance tests `PROXIMITY` to the plants as a risk factor. As mentioned above, the four weapons sites used were Los Alamos National Laboratory (NM), Nevada Test Site (NV), Rocky Flats Plant (CO), and Savannah River Site (SC). SAS "estimate" options delivered comparisons among levels of independent variables.

Spatial Variables: Ecologic Region and Case/Control

In the original tables, in some cases, a new subject would be submitted to the Autopsy Project from a participating pathologist, and a data table was not open for that subject's home area. In that case, data for the subject were added to the New Mexico and Others table, which was always open. For instance, subjects from California, Michigan, Nebraska, Maryland, Pennsylvania, New Jersey and North Carolina, to name a few, are found in the "New Mexico and Others" table. In analyses comparing one region with another, this table was used as a whole representing New Mexico. This misclassification error may have contributed to the inability of previous studies to detect regional differences. Some of these, such as Maryland and California, did not fit easily into the seven-table schema devised by the original research group. For this project, a new schema is developed in which `CITY_OF_RESIDENCE` is used to reassign subjects to nine more ecologically uniform regions. `REGION` is included in the online database but was not used as an independent variable. Instead, `REGION` assignments aided in classifying subjects into `CNTLGROUP`s.

The variable `CNTLGROUP` represents control group, distinguishing between regions which surround and are downwind of nuclear weapons facilities (case areas), and those which are far distant (control areas). In this dataset, we have reclassified the subjects from the original seven tables to the following Case/Control regions:

Case:
City of Los Alamos (LANL)
Greater New Mexico and Texas (cities of Anton, Dallas and Sherman) (LANL)
Colorado (includes Wyoming, Nebraska) (RFP and NTS[6])
Georgia, South and North Carolina (SRS)

Control:
Pacific (California)
Gulf Coast (Louisiana)
Upper Midwest (Michigan, Indiana and Illinois)
Eastern Interior (Ohio, Western Pennsylvania and West Virginia)
Mid-Atlantic (Eastern Pennsylvania, Maryland, New Jersey and New York)
New England and Maritime (Nova Scotia, Canada)

Distributions

Following are selected multiway crosstabulations which depict the effect-partitioned denominators of the analysis dataset. The map shows locations of all the cities of residence in the study, and the locations of the four nuclear weapons sites.

Control Group, Time and Gender. Table 2 displays the number of observations in each group by year of death, control group and gender, out of the subset of observations chosen to enter the model. Records for 680 subjects out of 710 lung samples were found sufficiently complete to enter the model and not likely to be erroneous, as detected by outlier analysis. The number of subjects entered in the project increases substantially in the years after the LNTBT, especially from 1968 forward. On Table 2, note that there was a two-year hiatus in collecting samples between 1964-65, after the Limited Nuclear Test Ban Treaty went into effect. Also note that the Total column on the right became quite large after 1966, compared with before. Before the hiatus, only 58 subjects had been acquired in the analysis subset. Afterwards, 622 were received. Also, in 11 years out of 16, men outnumbered women. In the grand total, the M/F ratio is about 1.7.

US State and Year of Death. Table 3 displays the number of subjects collected over the span of the Autopsy Project, by subject's year of death, region, and state.

Range of Dependent Variable, Plutonium Decays/Minute/Kg Standard Lung. Tables 3 and 4 display the range and frequencies of values of `LUNG_ACTSTDORG`, the measure of plutonium dpm/kg in lung tissue. The range of values lies between 0.0035 (the value substituted for <MRL results) and 7.53 dpm/kg of standard lung. Table 5 displays the distribution of values in nine intervals, by case and control group. Frequencies of "Analysis Not Available" observations are included for comparison. The overall mean is 0.72 dpm/kg, and the distribution is skewed far left, typical for gamma distributions.

Sources of Uncertainty

Up to this point, the statistical decisions were fairly standard. There were the things we knew, the assay values, and the things we didn't know, the random variation. But there were also sample codes in place of decay counts which caused gaps in the distribution of the dependent variable. This created an unusual situation which affects the interpretation of the findings. In this database, two kinds of unknowns are present: samples whose radioactivity fell beneath the detection level of the spectrometers used at the time ("below the minimum detectable level", "<MRL") and samples which had not been analyzed at publication ("Analysis Not Available"). In this study, "<MRL" observations were retained for the analysis, but "Analysis Not Available" observations were not (Figure 1).

<MRL. The first unknown is common to almost all sets of radioassay data: those samples which do not possess a level of radioactivity sufficient to be detected by available instruments. McInroy et al. reported a minimum detection limit of 0.017 decays per minute (dpm), obtained by taking the 99^{th} percentile of net activity.[1] In these data, a number of samples either failed to give off a detectable reading for the alpha spectrometers of the time, or were truly stable. It is impossible to draw a line between the slightly radioactive and the completely stable sample in this group. Of course, the distribution of values within this category is also not known.

These <MRL values were recoded to 0.0035 dpm, which represents a postulated average for the <MRL group. A sensitivity analysis testing values of 0.002, 0.005 and 0.008 dpm produced only trivial differences between those results and the results reported here. Table 4 shows readable samples for 368 in the case group and 113 subjects in the control group. The <MRL cells for case and control contain 100 and 99 observations, respectively.

Alpha activity is measured in an alpha spectrometer, from sample residue electroplated onto a stainless steel planchet. An aliquot of the original sample is taken, and this portion is "spiked" with a known quantity of the radionuclide of interest (here, 0.1 dpm Pu-239), capable of lifting the actual radioactivity level of the sample up past the threshold of detection. A known quantity of radioactive tracer is also added, to include an extra nuclide to assess the chemical recovery of the plutonium isotopes. Then the sample is wet- and dry-ashed until the plutonium can be completely dissolved in acid. This solution is then electroplated onto the planchet, which is placed in a silicon surface barrier detector, which records the counts. The count contributed by the tracer is subtracted from the total counts, leaving the radioactive amount of the sample as the remainder. Each radionuclide gives off alpha emissions of specific quantities of energy. For example, plutonium-239 emits alpha particles at 5.16 MeV, while plutonium-242 emits at 4.9 MeV. Accuracy and specificity of counts are affected by how large the aliquot size is, how large the silicon surface barrier detector is, and how long the sample is permitted to remain in the detector.

The Autopsy Plutonium project was instrumental in developing radioassay techniques for measuring tissue samples of exposed persons, and experienced its own learning curve as it gained experience. In 1974, the investigators decided to replace Plutonium-236, which they had been using as a tracer, with plutonium-242. Pu-236's half-life was very short (2.8 years), and its decay products also produced emissions with energies nearly equal to the plutonium isotopes of interest. Pu-242 has a half-life of 375,800 years with energies ranging between 4.7 and 4.9 MeV, with its 4.9-MeV emission happening 78% of the time. Pu-239's half-life is 24,131 years and its alpha emissions range between 5.0 and 5.15 MeV, with the 5.15 MeV signature occurring 73% of the time. Hence, the Pu-242 decays much more slowly, minimizing contamination of the sample with progeny, and its energy signature is easy to separate from those of the Pu-239 emissions.

The same year, the project modified its ion-exchange procedure to accommodate larger sample aliquots. The following year, they changed the electroplating procedure to use an ammonium sulfate electrolyte. They also increased the diameter of the plating area to 1 cm, and electropolished the planchets before use. In 1978 they altered the chemistry of the nitric acid solution to achieve more complete dissolution of the plutonium isotopes. Taken together, these changes improved considerably the accuracy and specificity of counts. The resultant procedure used a 300-mm^2 silicon surface barrier detector and measured each planchet for 50,000 seconds.

Today's equipment uses 450-mm^2 silicon surface barrier detectors and counts the samples for 150,000 seconds. These changes have increased the sensitivity and reduced the variability in recorded counts. As mentioned above, McInroy et al. claimed a MDL of 0.017 dpm, based on the 99^{th} percentile of net sample activity.[1] In conversation with Dr. James Elliston, who has done considerable work re-evaluating sampling accuracy in the "Plutonium in Autopsy Tissue" tissue sample archive, he suggested that this 0.017 dpm level reflected close to a "best-case" measurement, and was not likely the average or expected MDL value over the population of sample measurements. He expects today's alpha spectrometry readings to have a conservative or reasonable expectation of at least 0.017 dpm, and his best-case MDL to come in around 0.010.[22]

"Analysis Not Available." The second type of unknown is the notation "Analysis Not Available" found in place of radioassay values for many tissues during the years 1973-1976. The project director of the Los Alamos fallout plutonium in autopsy tissue study, Dr. McInroy, said that his team needed to get a publication into print in Health Physics describing the program before they had had sufficient time to analyze all the samples they had received.[8] Thus, for these samples, the authors noted that the samples had been received, but the assays had not been completed yet, using the label "Analysis Not Available". Since that time the assays have been completed but not published in open literature.

Figure 1 depicts the derivation of the study population for this model from the complete dataset of 901 observations. "Analysis Not Available" observations, numbering 90 cases and 88 controls, did not enter into the study population.

Deleted Observations. Two subjects were submitted with no state of residence given, so they were not classifiable as case or control, and were unavailable for this spatial analysis. Three subjects in the Control group had city and state assignments, but no lung sample in their submissions. Ten subjects' samples were either lost in analysis or not received (Figure 1).

Outliers. Members of the original Plutonium in Autopsy Tissue project concluded that a few of the tissue assay values were so unlikely as to be erroneous, and performed outlier statistical tests to identify which observations should be excluded from analysis.[10] Reasons given for erroneous results included contamination of equipment from a previous test, contamination of low-level samples with a high sample when the samples were processed together, and errors in observation, transcription or keypunching. Case numbers identified as likely possessing an erroneous measurement were published, along with information about which tissue reading was in error, what the erroneous reading was, etc. Eighteen lung samples were identified as outliers, 17 of which fall within the group of observations selected for this analysis. These 17 observations were therefore removed from the dataset used in this analysis.

The Model

Proc GENMOD selected 680 subjects out of the possible 693 as sufficiently complete in independent variable values to enter the model. The general linear model was run, with two levels of spatial organization, control group and individual weapons site within the case subgroup regions. Independent variables tested were weapons lab, case/control group, gender, age, proximity, year of death, and years residing in city of death. The model was composed as follows:

```
model lung_actstdorg = intercept(LANL) weapdum2(NTS) weapdum3(RFP) weapdum4(SRS) gender
age years_reside cntlgroup proximity y59-y63 y67-y75 / dist=GAMMA link=log ;
```

Los Alamos National Laboratory ("LANL") was specified as the reference site, because it has the greatest temporal coverage (Table 3). LANL 's coefficient corresponds to the intercept in the results.

Results

The chi-square goodness-of-fit test (Table 6) indicates by the Pearson Chi-Square score of 0.93 that the model represents the variation in the data quite closely.

Table 7 displays coefficients for each model term. Complete tables of parameter estimates and contrast statement requests from the statistical output are reproduced in Appendix A. Parameter estimates and probabilities associated with the chi-square of each independent variable were extracted from the table of parameter estimates, and a column of exponentiated coefficient estimates has been added for real-world-scaled discussion.

The coefficient estimate of the reference term, LANL, functions as the intercept coefficient in the regression equation. Its associated probability of <0.0001 reflects the likelihood that the intercept could be zero, which is remote. The next three terms (Nevada Test Site (NTS, weap_dum2), Rocky Flats Plant (RFP, weap_dum3), and Savannah River Site (SRS, weap_dum4) are small increments above LANL, and their probabilities are likelihoods that the coefficient estimate is significantly different from the LANL coefficient. These probabilities present no reasonable likelihood that subgroups from NTS, RFP or SRS regions have different plutonium lung burdens from the LANL subgroup at all (Table 7).

The next terms, GENDER, AGE, YEARS_RESIDE, and CNTLGROUP, are all highly significantly nonzero, and two of them, CNTLGROUP and GENDER, exert a strong influence on how much plutonium burden an individual will carry in his or her lung.

Aggregated into case/control groups, case subjects' lungs have an average 5.8 times the lung burden of plutonium compared with control subjects' lungs, holding all other variables to their means. This factor is highly significant, reporting a probability of less than 0.0001 that the two groups' means are equal.

An unexpected finding in this study is that males' lungs carried only about three-fourths the plutonium burden that females' lungs carried. The factor was 0.7377 – if females in a community are found to have an average of 'x' d/m Pu, then males' Pu burden will be 0.7377x d/m/kg, with a remote likelihood – p=0.01 – that the difference was zero. Radiobiological results have usually found males' lung burdens higher than females' during this time period, due to higher smoking prevalence rates among males.[7, 9] Therefore, the model was crafted anticipating the male excess. To obtain the factor in terms of female excess, the male factor is inverted: 1/0.7377 = 1.35, or women's lung burdens in this study population was 35% higher than males'.

Time trend analysis can be made by inspecting the exponentiated coefficient estimates for variables y59 through y75. The year 1975 was used as the reference year, and all previous years scaled in relation to it. As an example, one can see that the year 1960 saw all samples received to return an average of 14 times the plutonium lung burden of the 1975 sample group; the 1973 sample group averaged only 2.14 times the burden of the 1975 group. The elevated plutonium burdens are evident in the pre-test ban years of 1959 through 1963, and even in 1967, likely due to plutonium's persistence and resuspendibility in the environment.[7, 9] Thereafter, decreases in plutonium exposure in the general public become evident. The remainder of the variation in average burden from year to year is largely due to the areas sampled (see Table 3). It is noteworthy to observe that every estimated annual coefficient is highly significantly nonzero, and an important contributor to overall model fit.

Discussion

Inhalation is the most hazardous plutonium exposure in terms of generating health effects. Atmospheric weapons testing and nuclear weapons production released plutonium and other transuranic particles in a wide range of sizes, but many of them were 10 micrometers and smaller, which are highly prone to being inhaled and retained in the lung. Some particles will be expelled from the lung by ciliac action. Patients with depleted cilia, such as smokers and severe asthmatics, will have greater difficulty in expelling plutonium particulates. In the lung, the chemical composition of the particle controls how quickly lymphatic fluid can mobilize and remove it to the lymph nodes and thereon into the blood stream, to be deposited into other organs. Some particles of plutonium will not dissolve quickly, and will remain in unciliated parts of the lung for long periods. From the lymph nodes, the most common destinations are liver and tribecular (spongey) bone, although kidneys, gonads, brain, spleen, heart, striated muscle and other organs have also yielded plutonium deposits.[9, 11]

This approach, partitioning this historic database into case/control regions, gender blocks and year-of-death strata, linking a log-linear structure and applying a gamma distribution to accommodate the data's structure, has yielded some new conclusions. People living in the environs of a nuclear weapons site (median distance 16 miles, mean 25 miles, 99th percentile upper bound, 200 miles), could expect to carry (plus or minus) six times as much plutonium in their lungs as their more distant fellow Americans (mean distance 600 miles, range 200-1200 miles), which difference carried a significance level of <0.0001. Correcting areal classifications likely account for some strengthening of findings over previous studies.

Retained plutonium in the lung is transitory, decreasing over time as it is either expelled or dissolved and carried to other parts of the body. Women's lungs did not appear to purge themselves as readily as men's through the study period: their burdens were 35% higher, with the likelihood that the true difference is null, equal to 0.0129. This is also contrary to published reports,[7, 9] due to the fact that women's smoking levels were usually much lower than men's during the study period. In this study, this finding could be due to the fact that the number of female subjects was much lower, and pre-test ban samples formed a larger proportion of the total female population (26%), than pre-test ban male samples (15%), based on a dividing line set after 1967. Also, the male case/control proportion is 1.74, while the female is 3.0, so case subjects dominate the female subgroup to a greater extent than the male.

This analysis also corroborates established findings: The older one is before one dies, the higher one's plutonium burden becomes. If one's city of residence is in an area of exposure to airborne plutonium, the longer one resides there also correlates with increases in lung burden. Both of these factors are highly significant.

It is prudent to regard these results as preliminary. Increasing the number and quality of sample values by filling in the "Analysis Not Available" fields is expected to strengthen this study's findings somewhat. The original study's laboratory notebooks are available for copy from the United States Transuranium and Uranium Registries at Washington State University, Pullman, Washington, US, where the tissues are now archived. Sample counts for the 178 "Analysis Not Available" subjects are believed to be recorded in these notebooks, and a request has been made to the Registries for a copy. This database will be updated with these additional values as soon as possible, and a revision to these findings will be made.

This study supports Shonka's finding[4] that the Autopsy Tissue database can be a valuable tool in reconstructing population exposure from weapons production and testing activities. Resumption of weapons activities at these locations can be expected to amplify the contamination pattern.

To maximize the utility of this historic database, the <MRL assays should be recounted using a modern alpha spectrometer. Recounting the "<MRL" samples can potentially supply a greater range in the distribution of the lower-dose readings. Outliers identified as possibly due to contamination of lab equipment, such as the stainless steel planchets,[10] can also be recounted in new equipment.

Overall, the parameter coefficients tell a familiar story, and a more emphatic story than first told in "Plutonium in Autopsy Tissue":[1] Lung burdens throughout the study area, in case and control regions alike, demonstrate that all Americans have been at risk for plutonium inhalation from both nuclear weapons testing and weapons fabrication. The time trend analysis offers evidence that plutonium in minute particle sizes can remain available for inhalation for many years. Living within 200 hundred miles of a nuclear weapons facility poses a threat up to 6.8 times as great as living at much greater distances. This was true whether the facility was a testing ground or a factory. Atmospheric weapons tests were extremely hazardous to the general public's health, and levels of lung contamination did not start to decline until about five years after they were stopped. The importance of factors such as age, length of residence near the weapons site before dying, and the marked decline in lung burden over time are also corroborated. The fact that this treatment reaffirms established conclusions speaks to the general reliability of the model used in this study. Fine-tuning some of the data fields will confirm the values of coefficients and might improve probabilities, but the fundamental conclusions can be expected to remain the same.

Endnotes

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TABLES

Table 2. Analysis Dataset: Subjects (N, n) by Control Group, Gender and Year of Death
Plutonium in Autopsy Tissue Data Re-analysis

Table of YEAR_DEATH by CNTLGROUP by GENDER

YEAR_DEATH	CASE			CONTROL			Total
Frequency	Male	Female	Missing GENDER	Male	Female	Missing GENDER	
.	0	0	1	0	0	0	1
1959	1	1	0	0	0	0	2
1960	6	7	0	1	2	0	16
1961	5	8	0	1	1	0	15
1962	7	11	0	0	0	0	18
1963	4	2	0	0	0	0	6
1966	0	1	0	0	0	0	1
1967	11	5	0	1	0	0	16
1968	8	1	0	30	2	1	42
1969	11	9	0	0	1	0	21
1970	16	16	0	1	0	0	33
1971	53	20	0	0	0	0	73
1972	49	29	1	1	0	0	80
1973	26	13	1	0	4	0	44
1974	40	27	2	27	18	0	114
1975	36	27	0	72	35	0	170
1976	8	6	0	13	1	0	28
Total	281	182	5	147	64	1	680

Table 3. Spatial Coverage By Year and Number of Observations
Plutonium in Autopsy Tissues Analysis Dataset

REGION	STATE	N
------------ YEAR_DEATH=. ------------		
Georgia, South and North Carolina	GA	1
------------ YEAR_DEATH=1959 ------------		
Los Alamos	NM	2
------------ YEAR_DEATH=1960 ------------		
Greater New Mexico and Texas	NM	3
Gulf Coast	LA	1
Los Alamos	NM	10
Mid-Atlantic	PA	1
New England and Maritime	NS	1
------------ YEAR_DEATH=1961 ------------		
Greater New Mexico and Texas	NM	1
Los Alamos	NM	12
Mid-Atlantic	NJ	2
------------ YEAR_DEATH=1962 ------------		
Colorado	NE	1
Georgia, South and North Carolina	NC	1
Greater New Mexico and Texas	NM, TX	8
Los Alamos	NM	8
------------ YEAR_DEATH=1963 ------------		
Greater New Mexico and Texas	NM	3
Los Alamos	NM	3
------------ YEAR_DEATH=1966 ------------		
Greater New Mexico and Texas	NM	1
------------ YEAR_DEATH=1967 ------------		
Greater New Mexico and Texas	NM	9
Los Alamos	NM	6
Mid-Atlantic	NY	1
------------ YEAR_DEATH=1968 ------------		
Greater New Mexico and Texas	NM	4
Los Alamos	NM	5
Mid-Atlantic	NY	33
------------ YEAR_DEATH=1969 ------------		
Greater New Mexico and Texas	NM	11
Los Alamos	NM	9
Pacific	CA	1
------------ YEAR_DEATH=1970 ------------		
Colorado	CO	11
Greater New Mexico and Texas	NM	15
Los Alamos	NM	6
Upper Midwest	MI	1

Continued . . .

Table 3. Spatial Coverage By Year (continued)
Plutonium in Autopsy Tissues Database

REGION	STATE	N
------------ YEAR_DEATH=1971 ------------		
Colorado	CO	62
Greater New Mexico and Texas	NM	8
Los Alamos	NM	3
------------ YEAR_DEATH=1972 ------------		
Colorado	CO	42
Georgia, South and North Carolina	GA, SC	17
Greater New Mexico and Texas	NM	12
Los Alamos	NM	8
Pacific	CA	1
------------ YEAR_DEATH=1973 ------------		
Colorado	CO	26
Greater New Mexico and Texas	NM	12
Los Alamos	NM	2
Pacific	CA	1
Upper Midwest	IL	3
------------ YEAR_DEATH=1974 ------------		
Colorado	CO	9
Eastern Interior	OH, PA	36
Georgia, South and North Carolina	GA, NC, SC	60
Mid-Atlantic	MD	1
Upper Midwest	IL, IN	8
------------ YEAR_DEATH=1975 ------------		
Colorado	CO, WY	39
Eastern Interior	PA, WV	79
Georgia, South and North Carolina	GA, SC	20
Greater New Mexico and Texas	NM, TX	1
Los Alamos	NM	3
Mid-Atlantic	MD, PA	3
Upper Midwest	IL, IN	25
------------ YEAR_DEATH=1976 ------------		
Eastern Interior	OH, PA	13
Georgia, South and North Carolina	GA	16
Mid-Atlantic	NY	1

Table 4. SUMMARY DISTRIBUTION OF LUNG SAMPLE TISSUE ASSAYS

By Sample Status and Case/Control Group

Plutonium in Autopsy Tissue Reanalysis - Analysis Dataset

LUNG_ACTSTDORG (Activity/kg standard org/m	LUNG(Lung Sample Status: Present/Absent)				
	CONTROL		CASE		
Frequency Percent	ANALYSIS NOT AVAILABLE	ASSAY AV AVAILABLE	ANALYSIS NOT AVAILABLE	ASSAY AVAILABLE	Total
.	88	0	90	0	178
0.01-231.82	0	113	0	368	481
<MRL	0	99	0	100	199
TOTAL	88	212	90	468	
GROUP TOTAL	300		558		858

Table 5. DETAILED DISTRIBUTION OF LUNG SAMPLE TISSUE ASSAYS

By Sample Status and Case/Control Group

Plutonium in Autopsy Tissue Reanalysis - Analysis Dataset

LUNG_ACTSTDORG (Activity/kg standard org/m	LUNG(Lung Sample Status: Present/Absent)				
	CONTROL		CASE		
Frequency Percent	ANALYSIS NOT AVAILABLE	ASSAY AVAILABLE	ANALYSIS NOT AVAILABLE	ASSAY AVAILABLE	Total
.	88 10.20	0 0.00	90 10.50	0 0.00	178 20.74
0.0035	0 0.00	99 11.54	0 0.00	100 11.65	199 23.19
0.01-0.09	0 0.00	1 0.12	0 0.00	1 0.12	2 0.23
0.1-0.59	0 0.00	67 7.81	0 0.00	179 20.86	246 28.67
0.6-0.99	0 0.00	18 2.10	0 0.00	69 8.04	87 10.14
1-1.99	0 0.00	12 1.40	0 0.00	74 8.62	86 10.02
2-2.99	0 0.00	7 0.81	0 0.00	21 2.45	28 3.26
3-3.99	0 0.00	5 0.58	0 0.00	9 1.05	14 1.63
4-5.99	0 0.00	1 0.12	0 0.00	10 1.16	11 1.28
6-8.99	0 0.00	2 0.23	0 0.00	5 0.58	7 0.81
TOTAL	88 10.20	212 24.71	90 10.50	468 54.54	
GROUP TOTAL	300 0.350		558 0.650		858 100.00

Table 6. Chi-Square Table

Plutonium in Autopsy Tissue Re-Analysis: Analysis Dataset

The GENMOD Procedure

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Pearson Chi-Square	413	385.2845	0.9329
Scaled Pearson X2	413	325.9092	0.7891

Algorithm converged.

Table 7. Results: Model Term Coefficients
Plutonium in Autopsy Tissue Re-Analysis: Analysis Dataset

Proc GENMOD: Dependent Variable: Lung_Actstdorg

The GENMOD Procedure

Exponentiated Estimate Column Added

Parameter	DF	Estimate	Exponentiated Estimate	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept	1	-8.4593	0.0002	-9.8596	-7.0589	140.19	<.0001
weap_dum2	1	0.1068	1.1127	-0.2670	0.4806	0.31	0.5755
weap_dum3	1	0.0852	1.0889	-0.2602	0.4306	0.23	0.6288
weap_dum4	1	0.1089	1.1151	-0.2683	0.4861	0.32	0.5715
GENDER	1	-0.3042	0.7377	-0.5439	-0.0645	6.19	0.0129
age	1	0.0095	1.0095	0.0039	0.0150	11.16	0.0008
years_reside	1	0.0078	1.0079	0.0009	0.0147	4.96	0.0259
CNTLGROUP	1	1.9160	6.7937	1.1924	2.6396	26.93	<.0001
INV_LN_DIST	1	0.3295	1.3903	-0.4222	1.0811	0.74	0.3903
y59	1	4.6614	105.78	3.2847	6.0380	44.04	<.0001
y60	1	7.1675	1296.6	6.0066	8.3283	146.44	<.0001
y61	1	6.3424	568.16	5.1849	7.4998	115.35	<.0001
y62	1	7.2297	1379.8	6.0873	8.3721	153.84	<.0001
y63	1	6.2035	494.48	4.9657	7.4414	96.48	<.0001
y67	1	7.1083	1222.1	5.9379	8.2787	141.69	<.0001
y68	1	5.9598	387.53	4.6157	7.3039	75.52	<.0001
y69	1	5.8582	350.09	4.7185	6.9979	101.50	<.0001
y70	1	6.1690	477.71	5.0113	7.3267	109.08	<.0001
y71	1	5.2631	193.08	4.1471	6.3792	85.43	<.0001
y72	1	5.6928	296.72	4.5751	6.8105	99.66	<.0001
y73	1	5.3021	200.76	4.1784	6.4258	85.52	<.0001
y74	1	5.4996	244.59	4.2393	6.7598	73.15	<.0001
y75	1	4.5408	93.766	3.0153	6.0663	34.04	<.0001
Scale	1	0.8459	2.3301	0.7539	0.9491		

APPENDIX A

STATISTICAL OUTPUT OF LUNG MODELS

PLUTONIUM AUTOPSY PROJECT :: Inferential Statistics

Proc GENMOD: Rita's' Model. Dependent Variable: Lung_Actstdorg
'<MRL' Counts Recoded to 0.0035

The GENMOD Procedure

Model Information

Data Set	WORK.CASE_4	
Distribution	Gamma	
Link Function	Log	
Dependent Variable	lung_actstdorg	Activity/standard organ in disintegratns/min

Number of Observations Read	2764
Number of Observations Used	436
Missing Values	2328

Parameter Information

Parameter	Effect
Prm1	Intercept
Prm2	weap_dum2
Prm3	weap_dum3
Prm4	weap_dum4
Prm5	GENDER
Prm6	age
Prm7	years_reside
Prm8	CNTLGROUP
Prm9	INV_LN_DIST
Prm10	y59
Prm11	y60
Prm12	y61
Prm13	y62
Prm14	y63
Prm15	y67
Prm16	y68
Prm17	y69
Prm18	y70
Prm19	y71
Prm20	y72
Prm21	y73
Prm22	y74
Prm23	y75

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	413	607.3896	1.4707
Scaled Deviance	413	513.7862	1.2440

Pearson Chi-Square	413	385.2845	0.9329
Scaled Pearson X2	413	325.9092	0.7891
Log Likelihood		-452.4272	

PLUTONIUM AUTOPSY PROJECT :: Inferential Statistics

Proc GENMOD: Rita's' Model. Dependent Variable: Lung_Actstdorg
'<MRL' Counts Recoded to 0.0035

The GENMOD Procedure

Algorithm converged.

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept	1	-8.4593	0.7145	-9.8596	-7.0589	140.19	<.0001
weap_dum2	1	0.1068	0.1907	-0.2670	0.4806	0.31	0.5755
weap_dum3	1	0.0852	0.1762	-0.2602	0.4306	0.23	0.6288
weap_dum4	1	0.1089	0.1924	-0.2683	0.4861	0.32	0.5715
GENDER	1	-0.3042	0.1223	-0.5439	-0.0645	6.19	0.0129
age	1	0.0095	0.0028	0.0039	0.0150	11.16	0.0008
years_reside	1	0.0078	0.0035	0.0009	0.0147	4.96	0.0259
CNTLGROUP	1	1.9160	0.3692	1.1924	2.6396	26.93	<.0001
INV_LN_DIST	1	0.3295	0.3835	-0.4222	1.0811	0.74	0.3903
y59	1	4.6614	0.7024	3.2847	6.0380	44.04	<.0001
y60	1	7.1675	0.5923	6.0066	8.3283	146.44	<.0001
y61	1	6.3424	0.5905	5.1849	7.4998	115.35	<.0001
y62	1	7.2297	0.5829	6.0873	8.3721	153.84	<.0001
y63	1	6.2035	0.6316	4.9657	7.4414	96.48	<.0001
y67	1	7.1083	0.5972	5.9379	8.2787	141.69	<.0001
y68	1	5.9598	0.6858	4.6157	7.3039	75.52	<.0001
y69	1	5.8582	0.5815	4.7185	6.9979	101.50	<.0001
y70	1	6.1690	0.5907	5.0113	7.3267	109.08	<.0001
y71	1	5.2631	0.5694	4.1471	6.3792	85.43	<.0001
y72	1	5.6928	0.5703	4.5751	6.8105	99.66	<.0001
y73	1	5.3021	0.5733	4.1784	6.4258	85.52	<.0001
y74	1	5.4996	0.6430	4.2393	6.7598	73.15	<.0001
y75	1	4.5408	0.7783	3.0153	6.0663	34.04	<.0001
Scale	1	0.8459	0.0497	0.7539	0.9491		

NOTE: The scale parameter was estimated by maximum likelihood.

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha	Confidence Limits		Chi-Square	Pr > ChiSq
male - female	-0.3042	0.1223	0.05	-0.5439	-0.0645	6.19	0.0129
Exp(male - female)	0.7377	0.0902	0.05	0.5805	0.9375		
NTS - LANL	0.1068	0.1907	0.05	-0.2670	0.4806	0.31	0.5755
Exp(NTS - LANL)	1.1127	0.2122	0.05	0.7657	1.6170		
RFP - LANL	0.0852	0.1762	0.05	-0.2602	0.4306	0.23	0.6288
Exp(RFP - LANL)	1.0889	0.1919	0.05	0.7709	1.5382		
SRS - LANL	0.1089	0.1924	0.05	-0.2683	0.4861	0.32	0.5715
Exp(SRS - LANL)	1.1151	0.2146	0.05	0.7647	1.6259		
NTS versus RFP	-0.0216	0.1493	0.05	-0.3142	0.2710	0.02	0.8850

Exp(NTS versus RFP)	0.9786	0.1461	0.05	0.7304	1.3113		
Case - Control	1.9160	0.3692	0.05	1.1924	2.6396	26.93	<.0001
Exp(Case - Control)	6.7937	2.5082	0.05	3.2949	14.0075		
Age Effect	0.0095	0.0028	0.05	0.0039	0.0150	11.16	0.0008
Exp(Age Effect)	1.0095	0.0029	0.05	1.0039	1.0152		

Contrast Estimate Results (Continued)

Label	Estimate	Standard Error	Alpha	Confidence Limits		Chi-Square	Pr > ChiSq
Gender Effect	-0.3042	0.1223	0.05	-0.5439	-0.0645	6.19	0.0129
Exp(Gender Effect)	0.7377	0.0902	0.05	0.5805	0.9375		
Years_Reside Effect	0.0078	0.0035	0.05	0.0009	0.0147	4.96	0.0259
Exp(Years_Reside Effect)	1.0079	0.0035	0.05	1.0009	1.0148		
proximity, exponentiated	0.3295	0.3835	0.05	-0.4222	1.0811	0.74	0.3903
Exp(proximity, exponentiated)	1.3903	0.5332	0.05	0.6556	2.9480		
Blow up vs Make	-0.0437	0.1154	0.05	-0.2699	0.1826	0.14	0.7053
Exp(Blow up vs Make)	0.9573	0.1105	0.05	0.7635	1.2003		
Test Ban	0.7139	0.1936	0.05	0.3345	1.0933	13.60	0.0002
Exp(Test Ban)	2.0420	0.3953	0.05	1.3973	2.9841		