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A Study Update of Mortality in Workers at a Phosphate Fertilizer Production Facility

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Abstract

Objective—To evaluate the mortality experience among 3,199 workers employed 1951–1976 at a phosphate fertilizer production plant in central Florida with follow-up through2011.

Methods—Cause-specific standardized mortality ratios (SMRs) for the full cohort were calculated with the U.S. population as referent. Lung cancer and leukemia risks were further analyzed using conditional logistic regression.

Results—The mortality due to all-causes (SMR = 1.07, 95% confidence interval [CI] 1.02–1.13, observed deaths [n] = 1,473), all-cancers (SMR = 1.16, 95%CI 1.06–1.28, n = 431), and a priori outcomes of interests including lung cancer (SMR = 1.32, 95%CI = 1.13–1.53, n = 168) and leukemia (SMR = 1.74, 95%CI = 1.11–2.62, n = 23) were statistically significantly elevated. Regression modeling on employment duration or estimated radiation scores did not show exposure–response relation with lung cancer or leukemia mortality.

Conclusion—SMR results showed increased lung cancer and leukemia mortality in a full cohort of the phosphate fertilizer production facility. There was, however, no exposure–response relation observed among cases and matched controls.

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AUTHOR CONTRIBUTIONS

All authors meet the authorship criteria: (1) substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; (2) drafting the work or revising it critically for important intellectual content; (3) final approval of the version to be published; and (4) agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Review and Approval

This research was approved by the Institutional Review Boards of the National Institute for Occupational Safety and Health (NIOSH).

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Keywords

phosphate fertilizer production; lung cancer; leukemia; standardized mortality ratios; exposure–response; occupational epidemiology

INTRODUCTION

The United States is the second leading manufacturer of phosphate-based fertilizers worldwide. Nearly all phosphate production occurs in the Florida peninsula, where the industry maintains the mineral rights to about 440,000 acres of Florida land and has a multi-billion dollar capital investment in the state. Phosphate mining and processing can involve occupational exposures to a number of hazardous substances including uranium and radon daughters [Rutherford et al., 1995; BEIR VI, 1999], sulfuric and phosphoric acids, and acid mists [Hsu et al., 2007a]; other inorganic mists containing sulfate, fluoride, ammonium, and phosphate [Hsu et al., 2007b] and aerosols containing technically enhanced, naturally occurring radioactive material (TENORM) [Birky et al., 1998; Kim et al., 2006]. In particular, plant processes included the economic recovery of uranium for U.S. nuclear weapons production in the 1950s [Greek et al., 1957].

Studies have been conducted on workers employed in the Florida phosphate industry. Checkoway et al. [1985] studied a large phosphate worker cohort (n = 22,323) assembled from the employment records of 16 companies involving mining and chemical processing. With 10% confirmed deaths, they found a small excess of lung cancer mortality among phosphate workers when compared to U.S. rates, but not to local rates. Elevated emphysema mortality among White and workers of other races was also reported. These results, however, were statistically significant for White males only. A later study of the cohort was conducted adding 14 years of vital status follow-up and the workers known to be deceased increased to 21% [Checkoway et al., 1996]. This study conducted limited exposure–response analyses using job-based surrogates of exposure. The authors reported weak trends of lung cancer risk with alpha and gamma radiation among White males, and the overall conclusion was no large excesses of lung cancer mortality or other diseases related to workplace exposures.

Stayner et al. [1985] conducted a retrospective mortality study of 3,199 phosphate fertilizer production workers with follow-up through December 31, 1977. The study did not reveal an overall excess in cause-specific mortality in the population; however, a statistically significant excess of lung cancer among men of races other than White with greater than 10 years of employment and follow-up (SMR = 4.11, $P < 0.05$) was observed. Sixty percent (3/5) of the lung cancer cases among workers of other races were first employed as clean-up men, a job that 59% of this subpopulation had held. By comparison, only 1% of Whites had held this position, involving cleaning the phosphoric acid reaction vessel, which had potential for exposures to uranium and radon daughters. Although suggestive, these results were tempered by the fact that only 5.5% of the study population was known to be deceased at time of follow-up and there were few lung cancer cases (n = 10) observed. Moreover, the

study had limited work history and exposure information; thus, exposure response was not examined.

Block et al. [1988] found significant excesses of lung cancer (SMR = 1.62) and emphysema (SMR = 2.19) among White men (n = 2,607) employed by a Florida phosphate company between 1950 and 1979. Also observed was an increasing trend in lung cancer risk with increasing employment duration among workers accruing 20 years or more since first exposure. Like the preceding studies, only a small portion (14%) of the study population was deceased at time of follow-up [Block et al., 1988].

The current study reexamined the cause-specific mortality patterns among the cohort of phosphate fertilizer production workers originally studied by Stayner et al. [1985] with more work history information collected in 2007 and an additional 34 years of vital status follow-up through December 31, 2011. Additionally, because exposure to radiation has been linked to certain cancers [IARC Monograph Volume 100D, 2012], the possible connection between radiation exposures among phosphate fertilizer production workers and excesses in cancers, specifically lung cancer and leukemia, was also evaluated using a newly developed exposure assessment for radiation in a nested case–control study design. Potential confounding by co-exposures to acid mists and solvents was also considered in these analyses.

MATERIALS AND METHODS

Cohort Definition

A detailed description of the cohort is provided in the previous study [Stayner et al., 1985]. Briefly, the cohort included 3,199 workers who were employed at least one day from 1951 to 1976 at a now defunct phosphate-fertilizer production facility in central Florida. Demographic information including name, social security number, birth date and race as well as occupational histories including dates employed and job titles were obtained from personnel records. For race, White was coded as “White,” whereas all other races such as African-American, Asian, and Other were coded as “Other Races.” Vital status was updated through 2011 using the National Death Index (NDI), Social Security Administration (SSA) mortality database, and other available databases such as LexisNexis. Underlying cause of death (UCOD) information was coded according to the International Classification of Diseases (ICD) revision in effect at the time of death. The loss of follow-up was 2% (n = 63).

Outcomes of Interest

Cancer cases were defined by UCOD. Respiratory cancers and non-malignant lung disease (e.g., emphysema) were a priori outcomes of interest because of elevations observed in previous studies of this cohort [Stayner et al., 1985] and other phosphate worker populations [Checkoway et al., 1985; Block et al., 1988; Checkoway et al., 1996]. Exposure to strong inorganic acid mists containing sulfuric acid has been linked to excess lung cancer and laryngeal cancer [Steenland et al., 1988; Steenland and Beaumont, 1989; Steenland, 1997]. Leukemia mortality was also of interest because of its known association with ionizing radiation and for having few other known risk factors. A potential exception is some solvents

that are known or suspected leukemogens [Schottenfeld and Fraumeni, 2006]. Although there was no evidence of widespread use in plant processes, these solvents may have been used by some workers in the course of their employment at the plant. Common solvents include laboratory reagents, equipment degreasers, cutting fluids, and paint thinners used by laboratory workers, mechanics, machinists, carpenters, and painters.

Exposure Assessment

Low-level exposure to ionizing radiation from radio-nuclides in the uranium decay series was likely for phosphate workers throughout their careers, particularly during uranium extraction operations in early years because of direct involvement with uranium compounds during recovery processes. Information gathered from routine plant operations suggested that the average annual total effective dose equivalent (TEDE) resulting from occupational TENORM exposure is below 1.0 mSv. The TEDE primarily stems from inhalation of TENORM suspended in airborne dusts and from short-lived radon decay products. More detailed work history information was collected in 2007. An extensive search for information has not revealed a means to identify uranium extraction workers (other than dates of operation), radiation dosimetry, or survey records related to extraction operations. In the absence of these data, we estimated radiation by job titles with exposure potential. Similarly, job titles were also used to develop exposure estimates for solvents and acid mists.

The exposure assessment was conducted by an industrial hygienist who was blinded to case status. Direct information on individual worker occupational exposures was not available; therefore, surrogates for exposure were developed from existing employment histories and process knowledge. Primary agents of interest were ionizing radiation and potential confounders such as acid mist and solvents. Job exposure matrices (JEMs) were developed to evaluate combinations of work duration, job titles, and department assignments. This information was used to calculate exposure “scores” for each work interval. For each worker, a score for the ith work interval was calculated as the product of exposure level (L_i), interval duration (D_i) in days, supervisory status (S_i), and a calendar period weighting factor to account for improvements in protective standards and engineering controls over time (T_i). The value for L_i was selected from an ordinal set of values (i.e., L_i 0, 0.1, 0.5, or 1) representing a gradient in exposure intensity based on job assignment and the exposure agent of interest. The value for S_i was assigned 0.5 for supervisory and 1 for non-supervisory production workers to indicate a general decrease in exposure potential among supervisory personnel. The selection of a value for T_i was consistent with the time-dependent weighting scheme used by Henn et al. [2007]. For each worker and exposure surrogate, cumulative exposure scores were calculated by summing interval values from age at first exposure to attained age minus any imposed exposure lag period.

Statistical Analysis

External comparisons of mortality rates were made using the NIOSH Life Table Analysis System (LTAS.NET). Observed deaths were classified into 1 of 92 cause-of-death categories [Robinson et al., 2006]. The expected numbers of deaths were estimated for all-deaths combined, all-cancer deaths combined, and each cause-specific death category as the product of U.S. population death rates and the person years at risk of dying (PYARS) in

strata of race (White, all others), sex, and 5-year periods of age and calendar time [Schubauer-Berigan et al., 2011]. Death rates were available beginning in 1940 for most cancers of interest and beginning in 1960 for non-Hodgkin's lymphoma and multiple myeloma. Observed deaths and PYARS were accumulated from the later of the date of first hire or the year of rate availability through the end of the study (December 31, 2011), date lost to follow-up, or the date of death, whichever occurred first.

Numbers of deaths observed for each cause were divided by the expected number of deaths to calculate standardized mortality ratios (SMRs). SMRs were also calculated by duration of employment categories (0–<1, 1–0<10, 10–<20, and 20+ years) and length of follow-up/time since first employment (TSFE) categories (0–<20, 20–<30, and 30+ years) for lung cancer mortality among males and leukemia mortality among White males.

LTAS.NET was used to conduct stratified internal comparisons of the relation between lung cancer and leukemia mortality and employment duration. Standardized rate ratios (SRRs) were calculated for strata of employment duration whereby the SRR is the ratio of the directly standardized stratum rate to the rate in the lowest exposed stratum (0–<1 years). As an internally adjusted comparison of rates, the SRR analysis is better suited for analysis involving across strata comparisons.

Stratified SMR and SRR analyses by duration of employment and TSFE were conducted for lung cancer among males and leukemia among White males. The analyses were not performed for females (3 lung cancer and 2 leukemia deaths) or leukemia among males of other races (1 death) as there were few deaths. Two-sided 95% confidence intervals (CIs) on the SMRs and SRRs and 2-sided tests of linear trend SRRs were conducted as described elsewhere [Steenland et al., 1990].

Nested Case–Control Modeling Analysis

For the nested case–control design, conditional logistic regression analyses were conducted to examine the relation between estimated occupational exposures to radiation and select outcomes with adjustment for potential confounders of other occupational exposures (e.g. acid mist in lung cancer and solvent in leukemia mortality). Multicollinearity among exposure metrics was examined by regression diagnostics [Davis et al., 1986]. An additional criterion of working 30 days or more was applied in selecting cases and controls. Risk sets were defined for each case of interest to include all other cohort members who were under observation and who lived to an age equal to or greater than the age of the case at death. A ratio of case to controls of 1:5 for lung cancer and 1:l0 for leukemia was used [Bertke et al., 2013], with all exposures received by the controls truncated at the age attained of the case. Model estimates included two-sided 95% profile likelihood confidence intervals. All models were also adjusted for sex, race, and birth cohort. Birth cohort effects were estimated using continuous variables constructed from terms calculated by restricted cubic splines with three knots at the 10th, 50th, and 90th centiles of birth year [Harrell, 2001]. Alternative models with duration or estimated exposure scores with lags of 10 years for lung cancer and 2 years for leukemia were also evaluated. All modeling was conducted using SAS Software, Version 9.1.3 [SAS Institute, Inc., 2007].

RESULTS

There were 3,173 workers with complete data available within the study period for analyses. The cohort is predominantly male (93%) and White (78%). Over half of the workers were short-term with less than 1 year of employment duration (n = 1,711). Compared with only 176 (5.5%) workers known to be deceased in the original study, the current study observed 1,473 deaths (46%) with over 3 decades of extended follow-up (Table I).

Among the 431 cancer deaths, 168 (including 124 White males, 3 White females, and 41 males of other races) died of lung cancer and 23 of leukemia (20 White males, 2 White females, and 1 male of other races). Twenty-nine lung cancer cases had employment duration less than 30 days, and thus were not included in the nested case–control analyses (Table II). All of the leukemia cases met the criteria of being employed 30 or more days and were included in the regression analyses.

SMR and SRR Analyses

A total of 124,363 person-years were accumulated in this cohort. There was a slight but statistically significant elevation in the all-cause mortality compared to the U.S. population. The mortality from all cancers was also statistically significantly elevated. Significant elevations were observed for the a priori outcomes of interests of lung cancer and leukemia as well as other outcomes such as other mental disorders and chronic obstructive pulmonary disease (COPD) (Table III). SMR results excluding workers with less than 30 days of employment were similar (results not shown).

When the full cohort was compared to the Florida population, the mortality from all causes (SMR = 1.09, 95%CI 1.03–1.14), all cancers (SMR = 1.17, 95%CI 1.06–1.29), lung cancer (SMR = 1.28, 95%CI 1.10–1.49), leukemia (SMR = 1.82, 95%CI 1.15–2.73), other mental disorders (SMR = 2.05, 95%CI 1.31–3.05), and COPD (SMR = 1.65, 95%C.I. 1.32–2.03) remained significantly elevated.

SMR results for White males were very similar to those for the entire cohort. It is not surprising that the results for White males resembled the overall cohort as they made up about 78% of the cohort. For males of other races, elevated SMRs were observed for all cancers (SMR = 1.25, 95%CI 1.03–1.51, number of deaths [n] = 109), multiple myeloma (SMR = 3.01, 95%CI 1.10–6.55, n = 6), and diabetes mellitus (SMR = 1.87, 95%CI 1.14–2.89, n = 20). The all-cause (SMR = 1.08, 95%CI 0.98–1.20, n = 386) and lung cancer (SMR = 1.37, 95%CI 0.98–1.86, n = 41) mortality was also elevated among males of other races. For White females, there was deficit in all-cause (SMR = 0.87, 95%CI 0.67–1.11, n = 65) and all-cancer (SMR = 0.57, 95%CI 0.30–0.97, n = 13) mortality, but an increase in other heart disease mortality (SMR = 2.32, 95%CI 1.00–4.58, n = 8). The SMR analysis was not reported for females of other races as there were less than five observed deaths.

Table IV shows stratified SMRs and 95%CIs by duration of employment and TSFE for lung cancer among males. Excess in lung cancer mortality was observed with 20–30 years of follow-up among White males with less than 1 year of employment and males of other races with 20+ years of employment. The leukemia SMRs among White males were elevated but

not statistically significant due to small numbers of deaths and resulting wide confidence intervals in all duration of employment and TSFE strata. There was no clear trend in lung cancer or leukemia mortality with increased duration of employment.

SRR analyses among male workers also failed to show an apparent increasing trend in mortality risk with increased duration of employment, with or without a lag of 10 years for lung cancer or 2 years for leukemia. As shown in Table V, SRR without a lag peaked at employment duration 10–<20 years, but dropped at the longest duration (20+ years). The overall results with a lag (not shown) followed the same pattern.

Nested Case–Control Modeling Analysis

In the nested case–control study analysis, the mean duration of employment without a lag was 6.8 years for lung cancer cases (n = 139) and 6.9 years for their matched controls (n = 695) as shown in Table VI. There was a slight difference in mean duration (5.9 for lung cancer cases vs. 6.2 years for controls) when a lag of 10 years was considered. Leukemia cases (n = 23) had longer mean duration of employment than the controls (n = 230) (7.0 vs. 5.6 years with or without a 2-year lag). There were slightly higher estimated mean radiation exposure scores from JEM among the lung cancer cases (2.3–2.5) than their controls (2.2–2.3) with or without a lag. The estimated mean exposure to radiation was also higher in leukemia cases (2.4) than in the controls (2.0).

There was little evidence of an association between lung cancer or leukemia mortality and employment duration or radiation exposure scores, with or without a lag, in the conditional regression analyses with adjustment for gender, race, birth cohort, and potential confounder (Table VI). Multicollinearity was not evident among estimated radiation, acid mist, and solvent scores. The relative risks per year of employment were 0.98 for lung cancer and 1.03 for leukemia, with or without a lag. With estimated radiation exposure scores, the relative risks were 0.98 for lung cancer and 1.08–1.09 for leukemia, with or without a lag. Based on the log-likelihood scores and changes in radiation parameter estimates, the results showed birth cohort effects on both outcomes, and some impact of gender on lung cancer as well as race and solvent on leukemia. The model fit did not improve when an interaction of the estimated radiation score and hire indicator (prior or on/after 1960) was added.

DISCUSSION

The analyses presented here describe the mortality experience of a previously studied cohort of phosphate fertilizer production workers, with follow-up extended over 3 decades. The previous study did not find significant elevations in cause-specific mortality in the cohort, likely due to a relatively young population and shorter follow-up. With extended follow-up, higher mortality rates from all-causes, all cancers, lung cancer, leukemia, and some nonmalignant diseases (e.g., other mental disorders and COPD) were now apparent among these workers compared to the U.S. population. The new findings were likely attributable to increased statistical power from prolonged follow-up and aging of the population. Additionally, the improved ascertainment resulted in a reduction in the number of deaths of unknown cause (20 in 1,473 or 1.4%, vs. 16 in 155 or 10% in the previous study). Analyses by gender-race groups also showed differences in mortality by race among males. White

males had higher leukemia risk but lower multiple myeloma and diabetes mellitus risk than males of other races. Leukemia mortality was statistically significantly increased among 2,282 White males (SMR = 1.96, 95%CI 1.20–3.03, n = 20) but non-significantly decreased among 680 males of other races (SMR = 0.44, 95%CI 0.01–2.48, n = 1). On the contrary, multiple myeloma mortality was statistically significantly increased among males of other races (SMR = 3.01, 95%CI 1.10–6.55, n = 6) but not among White males (SMR = 0.90, 95%CI 0.25–2.31, n = 4). The differences were not apparent among females possibly because there were far fewer female workers in the cohort.

The previous study reported an excess of lung cancer mortality (SMR = 4.11, one-tail $P < 0.05$, n = 3) among males of other races with greater than 10 years of employment and follow-up. The increase, although not statistically significant, persisted in the current study (SMR = 1.36, 95%CI 0.55–2.79, n = 7) with 20+ years of employment and follow-up. Further dividing the follow-up to 20–<30 and 30+ years resulted in significant increases among male workers of other races with 20+ years of employment and 20–30 years of follow-up (SMR = 4.59, $P < 0.05$) as well as White males with the least amount of employment (0–1 years) and the same length of follow-up (SMR = 2.66, $P < 0.01$) (Table IV). Further examination with SRR analyses in Table V did not reveal any trend of increased mortality with increased employment duration in either race group.

It is known that a greater proportion (59%) of males of other races (vs. 1% of Whites) worked as clean-up men who were assigned to clean the phosphoric acid reaction vessel. Crushed phosphate ore was mixed with sulfuric acid in these vessels to produce dicalcium phosphate and gypsum as a byproduct, and once a year before 1975 workers entered the vessel to chip away gypsum deposits from the agitator [Stayner et al., 1985]. This was thought to be the primary exposure to potential respiratory carcinogens that included chromium, arsenic, uranium, and radon daughters, and thus a potentially greater risk existed among males of other races. Our results in stratified SMR analyses showed that males of other races still had higher lung cancer mortality risk, especially those with 20+ years of employment and 20–<30 years of follow-up. Lung cancer mortality, however, did not differ by race (SMR = 1.35, 95%CI 1.13–1.61, n = 124 among White males vs. SMR = 1.37, 95%CI 0.98–1.86, n = 41, among males of other races).

The excess in other mental disorders (SMR = 1.83, $P < 0.01$) was an unexpected finding. Among the 24 deaths in this category, the average age at death was 80, two-thirds (n = 16) were reported from the state of Florida, and 22 in recent years (1999–2011 using ICD-10). The SMR increased to 2.05 ($P < 0.01$) when Florida rates were used as the reference. A possible explanation is that there may be more reported cases in Florida, but there are also more healthy people of older age groups in the state that result in lowered age-adjusted mortality rates. Another possibility is diagnostic bias due to systematical misclassification by medical examiners or care providers unfamiliar with patients before death [Silverstein et al., 1988].

The study has a number of important limitations. First, direct information on individual exposures was not available. Instead, exposure–response modeling was conducted using surrogates of exposure derived from employment information. Although these methods are

common to worker studies, it is difficult to gauge their validity in the absence of direct measurement data. Our use of relatively crude surrogates increased the potential for misspecification of worker exposures that would likely attenuate estimated risk. Second, information on environmental and other occupational exposures was not available. Over half (54%) of the study population was employed less than 1 year; therefore, significant contributions to overall risk from exposures elsewhere are likely. Third, information on important lifestyle factors, such as tobacco use, was also lacking. In particular, lung cancer is strongly associated with smoking behavior; therefore, lung cancer risk estimates are largely uncertain without smoking information. It is noteworthy that mortality from cardiovascular diseases, which is also associated with smoking, was not elevated in this cohort suggesting that confounding by smoking is less likely. Finally, although some estimates were relatively precise, only modest associations were observed; therefore, results should be cautiously interpreted because small effects are more prone to potential biases.

This evaluation provided adequate follow-up to examine mortality from cancers with long latency. At the time of the initial analysis, 5.5% of the cohort was deceased, whereas in this updated analysis, 46% were deceased. This extended follow-up revealed modest, but statistically significant excess mortality for a number of outcomes of a priori interest. There is not, however, sufficient evidence to determine a causal association between any outcome and occupational exposure based on the limited information available in this cohort.

CONCLUSION

The cohort of 3,173 phosphate production workers employed between 1951 and 1976 with follow-up through 2011 showed statistically significantly elevated mortality in all-cause and all-cancer, lung cancer, and leukemia, when compared with the U.S. population. Neither stratified SMR analysis nor internal comparison with SRR analysis showed a trend of increasing mortality with increased employment duration. Conditional logistic regression analyses with lung cancer and leukemia cases and selected controls also failed to establish a statistically significant exposure–response relation with employment duration or estimated radiation exposure scores. Further studies in plants with similar exposures or with more information on environmental and lifestyle factors are needed to clarify the exposure–response relation.

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TABLE I

Demographics of Phosphate Workers Employed 1951–1976 With Follow-Up Through 12/31/2011

Characteristics	n (%)/mean (SD)
Sex	
Male	2,962 (93%)
Female	211 (7%)
Race	
White	2,484 (78%)
Other races	689 (22%)
Age at hire	
<30	2,186 (69%)
30–<45	875 (28%)
45–<60	110 (3%)
60+	2 (0%)
Mean age at hire (years)	27.3 (8.0)
Year of hire	
<1955	540 (17%)
1955–1959	617 (19%)
1960–1964	420 (13%)
1964–1969	750 (24%)
1970+	846 (27%)
Duration of employment (years)	
0–<1	1,711 (54%)
1–<10	939 (30%)
10–<20	284 (9%)
20+	239 (8%)
Mean length of employment (years)	4.6 (8.1)
Mean age at last follow-up (years)	66.5 (12.6)
Vital status (as of 12/31/2011)	
Alive	1,700 (54%)
Deceased	1,473 (46%)

SD, standard deviation.

TABLE II

Workers, Deceased, and Lung Cancer and Leukemia Cases Among Workers by Gender and Race

	Full cohort				Workers with 30+ days of employment			
Race/gender	**Total**	**Dead (%)**	**Lung**	**Leukemia**	**Total**	**Dead (%)**	**Lung**	**Leukemia**
Male—White	2,282	1,020 (45)	124	20	1,949	871 (45)	107	20
Male—all others	680	386 (57)	41	1	543	301 (55)	29	1
Female—White	202	65 (32)	3	2	183	60 (33)	3	2
Female—all others	9	2 (22)	0	0	8	2 (25)	0	0

TABLE III

Selected Mortality Among Phosphate Workers Employed 1951–1976 With Follow-Up Through 12/31/2011

Underlying cause of death	Observed	SMR	95%CI
All causes	1,473	1.07*	1.02–1.13
Tuberculosis	2	0.71	0.09–2.55
All cancers	431	1.16**	1.06–1.28
MN buccal cavity and pharynx	6	0.68	0.25–1.48
MN tongue	1	0.50	0.01–2.77
MN other parts of buccal cavity	2	0.96	0.12–3.47
MN pharynx	3	0.64	0.13–1.88
MN digestive organs and peritoneum	84	0.91	0.73–1.13
MN esophagus	13	0.99	0.53–1.70
MN stomach	10	0.91	0.44–1.68
MN intestine except rectum	25	0.86	0.55–1.26
MN rectum	2	0.32	0.04–1.14
MN biliary, liver, gall bladder	14	1.16	0.64–1.95
MN pancreas	19	0.98	0.59–1.53
MN respiratory system	173	1.30**	1.11–1.51
MN larynx	5	1.08	0.35–2.52
MN trachea, bronchus, and lung	168	1.32**	1.13–1.53
MN breast	3	0.64	0.13–1.86
MN male genital organs	38	1.34	0.95–1.84
MN prostate	34	1.24	0.86–1.74
MN other male genital organs	4	3.93*	1.07–10.1
MN urinary organs	22	1.24	0.78–1.88
MN kidney	12	1.28	0.66–2.23
MN bladder and other urinary organs	10	1.20	0.57–2.20
MN other and unspecified sites	58	1.21	0.92–1.56
MN skin	13	1.69	0.90–2.89
Mesothelioma	1	0.90	0.02–5.00
MN brain and other nervous system	9	0.97	0.44–1.83
MN connective tissue	2	0.96	0.12–3.45
MN lymphatic and hematopoietic tissue	47	1.34	0.98–1.78
Non–Hodgkin's lymphoma	12	0.90	0.47–1.58
Hodgkin's disease	2	1.13	0.14-4.09
Leukemia	23	1.74*	1.11-2.62
Multiple myeloma	10	1.47	0.70-2.70
Diabetes mellitus	39	1.09	0.77-1.48
Diseases of blood and blood-forming organs	6	1.08	0.40–2.34
Mental, psychoneurotic, and personality disorders	30	1.35	0.91–1.92
Alcoholism	6	0.65	0.24–1.42

Underlying cause of death	Observed	SMR	95%CI
Other mental disorders	24	1.83**	1.18–2.73
Disorders of nervous system and sense organs	33	1.07	0.74–1.51
Multiple sclerosis	1	0.64	0.02–3.58
Other nervous system diseases	32	1.10	0.75–1.55
Diseases of the heart	402	0.99	0.89–1.09
Rheumatic heart disease	1	0.24	0.01–1.33
Ischemic heart disease	312	0.98	0.88–1.10
Chronic disease of endocardium	8	1.29	0.56–2.53
Hypertension with heart disease	22	1.28	0.80–1.93
Other heart diseases	59	0.95	0.72–1.23
Other diseases of the circulatory system	95	0.92	0.74–1.12
Hypertension without heart disease	11	1.33	0.66–2.38
Cerebrovascular disease	64	0.97	0.74–1.23
Diseases of arteries, veins, pulmonary circulation	20	0.69	0.42–1.07
Diseases of the respiratory system	123	1.16	0.96–1.38
Pneumonia	21	0.74	0.46–1.13
Chronic obstructive pulmonary disease	87	1.54**	1.23–1.90
Asthma	3	1.38	0.28–4.03
Pneumoconiosis and other respiratory diseases	12	0.66	0.34–1.15
Diseases of the digestive system	71	1.14	0.89–1.43
Diseases of stomach and duodenum	3	0.72	0.15–2.11
Hernia and intestinal obstruction	1	0.37	0.01–2.06
Cirrhosis and other chronic liver diseases	34	1.04	0.72–1.46
Other diseases of digestive system	33	1.44	0.99–2.02
Diseases of the genitourinary system	16	0.65	0.37–1.05
Acute glomerulonephritis and renal failure	1	0.37	0.01–2.04
Chronic and unspecified nephritis and renal failure	8	0.54	0.23–1.06
Kidney infection	1	1.38	0.03–7.66
Other diseases of male genital organs	1	4.27	0.11–23.8
Other genitourinary diseases	5	0.90	0.29–2.11
Diseases of skin and subcutaneous tissue	2	1.35	0.16–4.87
Diseases of musculoskeletal system and connective tissue	2	0.51	0.06–1.85
Symptoms and ill-defined conditions	14	0.85	0.47–1.43
Accidents	88	1.05	0.84–1.29
Transportation accidents	50	1.19	0.89–1.57
Accidental poisoning	8	1.30	0.56–2.56
Accidental falls	4	0.42	0.11–1.07
Other accidents	25	1.01	0.65–1.49
Medical complications and misadventure	1	0.57	0.01–3.17
Violence	55	1.13	0.85–1.47
Suicide	31	1.19	0.81–1.68
Homicide	24	1.07	0.68–1.59

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Underlying cause of death	Observed	SMR	95%CI
Other causes[a]	41	0.90	0.64–1.22

SMR, standardized mortality ratio; CI, confidence intervals; MN, malignant neoplasm.

[a]Excluding 20 deaths with missing or unknown cause.

*Two-sided $P < 0.05$.

**Two-sided $P < 0.01$.

TABLE IV

Lung Cancer and Leukemia SMRs (95%CI) by Employment Duration and Time Since First Employment (TSFE) Among Males

	Employment duration (years)									
TSFE	**0–<1**		**1–<10**		**10–<20**		**20+**		**Total**	
Years	**n**	**SMR (95%CI)**	**n**	**SMR (95%CI)**	**n**	**SMR (95%CI)**	**n**	**SMR (95%CI)**	**n**	**SMR (95%CI)**
Lung cancer—all races										
0–<20	4	0.64 (0.18, 1.65)	6	1.24 (0.45, 2.69)	3	0.99 (0.20, 2.88)		–	13	0.92 (0.49, 1.58)
20–<30	26	2.25 (1.47, 3.30)**	9	1.18 (0.54, 2.24)	7	1.80 (0.72, 3.70)	9	3.07 (1.40, 5.83)**	51	1.96 (1.46, 2.58)**
30+	50	1.40 (1.04, 1.84)*	32	1.23 (0.84, 1.73)	11	1.40 (0.70, 2.50)	8	0.69 (0.30, 1.36)	101	1.24 (1.01, 1.51)*
Total	80	1.49 (1.18, 1.86)**	47	1.22 (0.90, 1.62)	21	1.42 (0.88, 2.17)	17	1.17 (0.68, 1.88)	165	1.36 (1.16, 1.58)**
Lung cancer—White										
0–<20	3	0.68 (0.14, 2.00)	5	1.20 (0.39, 2.81)	2	0.88 (0.11, 3.19)		–	10	0.92 (0.44, 1.70)
20–<30	21	2.66 (1.65, 4.07)**	9	1.42 (0.65, 2.69)	4	1.30 (0.35, 3.33)	4	2.17 (0.59, 5.57)	38	1.98 (1.40, 2.72)**
30+	35	1.33 (0.93, 1.85)	26	1.22 (0.80, 1.79)	9	1.38 (0.63, 2.62)	6	0.80 (0.29, 1.74)	76	1.23 (0.97, 1.54)
Total	59	1.53 (1.16, 1.97) **	40	1.26 (0.90, 1.71)	15	1.27 (0.71, 2.09)	10	1.07 (0.51, 1.97)	124	1.35 (1.13, 1.61)**
Lung cancer—other races										
0–<20	1	0.55 (0.01, 3.07)	1	1.44 (0.04, 8.04)	1	1.28 (0.03, 7.14)		–	3	0.91 (0.19, 2.67)
20–<30	5	1.36 (0.44, 3.18)	0	0.00 (0.00, 2.92)	3	3.65 (0.75, 10.7)	5	4.59 (1.49, 10.7)*	13	1.90 (1.01, 3.25)*
30+	15	1.57 (0.88, 2.59)	6	1.26 (0.46, 2.74)	2	1.48 (0.18, 5.33)	2	0.49 (0.06, 1.77)	25	1.27 (0.82, 1.87)
Total	21	1.40 (0.86, 2.14)	7	1.04 (0.42, 2.14)	6	2.03 (0.74, 4.42)	7	1.36 (0.55, 2.79)	41	1.37 (0.98, 1.86)
Leukemia—White										
Total	8	1.83 (0.79, 3.61)	7	1.95 (0.79, 4.02)	3	2.36 (0.49, 6.88)	2	2.05 (0.25, 7.39)	20	1.96 (1.20, 3.03)**

SMRs, standardized mortality ratios; CI, confidence intervals.

*Two-sided $P < 0.05$.

**Two-sided $P < 0.01$.

TABLE V

Lung Cancer and Leukemia SRRs (95%CI) by Employment Duration and Time Since First Employment (TSFE) Among Males

	Employment duration (years)								
TSFE	**0–<1**		**1–<10**		**10–<20**		**20+**		
Years	**n**	**Baseline**	**n**	**SRR (95%CI)**	**n**	**SRR (95%CI)**	**n**	**SRR (95%CI)**	**Trend slope, *P*-value[a]**
Lung cancer—all races									
0–<20	4	1.0	6	1.74 (0.47, 6.41)	3	1.19 (0.26, 5.43)		–	NR
20–<30	26	1.0	9	0.48 (0.21, 1.12)	7	1.03 (0.36, 2.93)	9	0.85 (0.33, 2.18)	1.31×10^{-5}, 0.78
30+	50	1.0	32	0.89 (0.57, 1.40)	11	1.02 (0.51, 2.03)	8	0.41 (0.19, 0.89)	-6.59×10^{-5}, <0.01
Total	80	1.0	47	0.81 (0.56, 1.18)	21	1.02 (0.61, 1.70)	17	0.76 (0.43, 1.35)	-9.21×10^{-6}, 0.35
Lung cancer—White									
0–<20	3	1.0	5	1.90 (0.42, 8.56)	2	1.14 (0.18, 7.12)		–	NR
20–<30	21	1.0	9	0.47 (0.19, 1.14)	4	0.49 (0.13, 1.82)	4	0.41 (0.13, 1.32)	-2.50×10^{-5}, 0.37
30+	35	1.0	26	0.94 (0.56, 1.58)	9	1.07 (0.50, 2.31)	6	0.50 (0.20, 1.24)	-5.26×10^{-5}, <0.01
Total	59	1.0	40	0.83 (0.55, 1.25)	15	0.86 (0.47, 1.58)	10	0.60 (0.29, 1.25)	-1.83×10^{-5}, <0.01
Lung cancer—other races									
0–<20	1	1.0	1	9.11 (0.57, 146)	1	1.54 (0.10, 24.7)		–	NR
20–<30	5	1.0	0	0.00 (NR)	3	5.72 (1.15, 28.4)	5	2.00 (0.55, 7.22)	NR
30+	15	1.0	6	0.85 (0.32, 2.25)	2	0.91 (0.20, 4.09)	2	0.30 (0.07, 1.40)	-9.50×10^{-5}, <0.01
Total	21	1.0	7	1.02 (0.39, 2.71)	6	2.38 (0.77, 7.37)	7	1.18 (0.44, 3.15)	1.43×10^{-5}, 0.51
Leukemia—White									
Total	8	1.0	7	0.94 (0.33, 2.68)	3	1.09 (0.27, 4.33)	2	0.79 (0.16, 3.92)	-1.20×10^{-6}, 0.22

SRRs, standardized rate ratios; CI, confidence intervals; NR, not reported due to cells with zero deaths.

[a]Trend slopes with Wald-based two-sided *P*-values (significance level of 0.05) for the change in SRRs with increasing duration.

TABLE VI

Summary Statistics and Model Results of Employment Duration and Radiation Exposure Scores

	Cases			Controls			Rate ratio[a]
	N	Mean (SD)	Range	N	Mean (SD)	Range	(95%CI)
Lung cancer							
Duration (years)							
No lag	139	6.8 (9.0)	0.09–33.9	695	6.9 (9.4)	0.09–43.0	0.98 (0.96–1.01)
10-year lag	139	5.9 (7.9)	0–31.2	695	6.2 (8.9)	0–43.0	0.98 (0.95–1.01)
Radiation (score)							
No lag	139	2.5 (3.7)	0–16.5	695	2.3 (4.0)	0–21.2	0.98 (0.93–1.04)
10-year lag	139	2.3 (3.3)	0–14.9	695	2.2 (3.8)	0–19.7	0.98 (0.92–1.04)
Leukemia							
Duration (years)							
No lag	23	7.0 (9.5)	0.09–32.8	230	5.6 (8.2)	0.09–39.2	1.03 (0.96–1.09)
2-year lag	23	7.0 (9.5)	0.09–32.8	230	5.6 (8.2)	0–39.2	1.03 (0.96–1.10)
Radiation (score)							
No lag	23	2.4 (3.3)	0–12.3	230	2.0 (3.4)	0–15.3	1.08 (0.90–1.28)
2-year lag	23	2.4 (3.3)	0–12.3	230	2.0 (3.4)	0–15.3	1.09 (0.91–1.29)

SD, standard deviation; CI, confidence intervals.

[a]Rate ratio for one unit of exposure with adjustment for sex, race, birth cohort, and potential confounder.