External Radiation Exposure and Mortality Among a Cohort of Uranium Processing Workers

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ABSTRACT

The purpose of the study was to investigate mortality in a cohort of 2514 white males employed in a uranium processing plant between 1942 and 1966 to evaluate: 1) mortality compared to the U.S. population, and 2) the relationship between external ionizing radiation and cancer and other diseases of the respiratory, digestive, genitourinary, and lymphatic systems.

Standardized Mortality Ratios (SMRs) were calculated for 56 causes of death. Annual external radiation doses were obtained from individual film badge readings. Poisson trend test statistics were computed using time-dependent cumulative doses. Dose-response estimates with likelihood based confidence intervals (CIs) were calculated using a stratified excess relative risk model.

Through 1993, 1056 deaths were ascertained. Population dose from external radiation was 120 Sieverts. Cumulative individual doses had mean of 47.8 mSv and median of 15.3 mSv. SMR with a 95% CI was 0.92 (0.86,0.97) for all causes and 1.10 (0.98,1.23) for all cancers; respiratory diseases, chronic nephritis, and lymphatic cancers were significantly elevated. Trend tests revealed a statistically significant increase of kidney cancers based on 11 deaths (p=0.02) with relative risk estimate per Sv of 12.9 with 90% CI (1.4,67.6).

The only disease of a priori interest with evidence of exposure related effect was kidney cancer. While this appears to be related to exposure to radium and its daughters resulting from high grade uranium ore processing prior to removal of the radium component, it must be considered provisional since external radiation exposure may be a surrogate for internal radiation dose or chemical exposures which were not considered in this study.

INTRODUCTION

Mallinckrodt Chemical Works developed the first commercial process for processing tonnage quantities of uranium ore and concentrating it into pure uranium oxide and uranium metal. Uranium processing operations began in 1942 in St. Louis, Missouri and shifted to Weldon Springs, Missouri in 1958 where they continued until production operations ceased in 1966. Radioactive materials at the two sites included uranium, radium and thorium which resulted in potential exposure to both internal and external ionizing radiation. Unique to the St. Louis site was the processing from 1946 through 1955 of pitchblende ore which was up to 60% uranium. Because of the radium present in this ore the potential exposure to external ionizing radiation was much greater than at other uranium processing plants. Workers who were employed in the early steps of refining prior to removal of the radium content of the ore were at greatest risk. One hundred twelve Mallinckrodt workers had a film badge reading of 50 mSv or more in a calendar year. The 50 mSv value is the current occupational limit for whole body exposure to external ionizing radiation in a calendar year. The unique exposure to pitchblende ore, the large number of workers exposed to 50 mSv or more of external ionizing radiation in a calendar year, and the long follow up of this cohort make it unique among populations of uranium processing workers.

The objectives of this historical retrospective cohort mortality study were to evaluate the mortality experience of this worker population compared to the U.S. population, and the relationship between external radiation dose and mortality from certain diseases. These diseases were malignant and nonmalignant diseases of the digestive, genitourinary, lymphatic and respiratory systems. Only white men employed at least 30 days were included in this study because they made up over 81% of the work force, and no women and few persons of color worked in process areas. Subsequent analyses will focus on the relationship between internal ionizing radiation dose and mortality.

MATERIALS AND METHODS

The study cohort was enumerated using contemporary plant records which included work history, payroll, security, medical and personal radiation monitoring records. The birth date, gender, race, dates of hire and termination, job titles, departments and plants were collected for each worker. These workers were employed in Mallinckrodt's Uranium Division, the part of the company dedicated to the uranium processing operations. Because the Uranium Division was only a portion of the chemical operations at Mallinckrodt, the fact of Mallinckrodt employment outside of the Uranium Division was also collected for each worker.

Vital status through December 31, 1993, was determined for each worker through searches of the data bases of the Social Security Administration, Pension Benefit Information, and National Death Index (NDI). Death certificates were sought for all individuals with an indication of death from any of these sources. The underlying cause of death and any cancer cause not identified as the underlying cause were coded to the eighth revision of the International Classification of Diseases, Adapted for Use in the United States (ICDA). For all analyses comparing the study population to national statistics, the underlying cause of death was used. Non-underlying cancer causes were included in all dose-response analyses of external radiation exposure since they were based on an internal reference group.

NDI gave no death indication. Because of the potential impact of chemical exposures encountered during employment in other operations at Mallinckrodt outside of the Uranium Division, Standardized Mortality Ratios (SMR) were also calculated stratifying the cohort on such employment.

Dose-response analyses investigated the relationship between cumulative whole body exposure and mortality using an internal comparison group. Time-dependent cumulative exposure (mSv) was stratified into the following groups: <5, 5-, 10-, 20-, 40-, 80-, 160+. These doses were lagged 10 years for all causes except leukemia for which a two year lag was used. The first phase of the dose-response analysis consisted of trend tests as a screening procedure for a dose-response relationship. Poisson trend statistics using the methods outlined by Breslow and Day (1) were calculated stratifying person-years at risk into 15 five-year age groups, eight five-year calendar periods, and two groups based on Mallinckrodt employment outside the Uranium Division. Finally, dose-response estimates, expressed as excess relative risk for each Sv increase in dose, were calculated for sites of a priori interest using an excess relative risk model where relative risk is of the form $1+ \beta*\text{dose}$. Maximum likelihood estimates of the parameters and likelihood-based 90 percent confidence intervals were calculated using Poisson regression techniques to model death rate as a function of dose and covariates. Since the interest was in identifying the upper bound on the risk, 90 per cent confidence intervals were calculated. Dose-response estimates were adjusted by stratifying on age, calendar period and, when relevant, Mallinckrodt employment outside the Uranium Division. For both the trend tests and the dose-response modeling, dose was modeled as continuous using the person-years weighted mean dose per cell calculated by dividing the total number of person-years accumulated in a cell by the total amount of cumulative dose accrued during those years. Trend tests were conducted using SAS, and SMR and Poisson regression analyses were performed with the Amfit and Datab modules of Epicure (2,3).

Since no information was available on smoking and alcohol consumption, confounding by these two factors could be investigated only indirectly by looking for positive associations between these factors and specifically selected disease outcomes. For smoking, the relationships between radiation dose and smoking-related cancers (4), non-malignant respiratory diseases excluding pneumonia, and circulatory diseases were evaluated. For alcohol consumption, liver cirrhosis was similarly evaluated.

RESULTS

Of the 3,259 workers identified as ever employed in the Uranium Division, 2,514 white males employed at least 30 days were included in the study cohort. The reasons for which workers were excluded from the study are presented in Table 1. Of the excluded workers, 74.6 per cent were women and 5.8 per cent were men of color. These two groups were excluded from the study because interviews with former workers in the Uranium Division indicated that neither group worked in process areas making their potential for exposure to external radiation minimal.

Selected characteristics of the study cohort are presented in Table 2. On average, a worker hired into the Uranium division in 1951 at the age of 30.3 years and worked in the division for 5.2 years. Two-thirds of the workers were hired before 1956, the year in which pitchblende processing ended. A quarter of the workers were employed in Mallinckrodt operations outside the Uranium Division. The mean length of follow up was 34.6 years (median 36 years), and over 90 percent of the cohort was followed at least 20 years.

A total of 87,757 person-years was accumulated through 1993. Through the end of 1993, 1,056 workers died (42 per cent). The average age at death was 65.1 years (median 66 years) after 29.7 years of follow up (median 31 years). Death certificates were obtained for 1,055 (99.9%). Among the 1,458 workers not known to be deceased, 45 were lost to follow up before 1979, the first year for which data are available from NDI. The remaining 1,413 workers were assumed to be alive at the end of the study. The average age of those not known to be deceased was 64.9 years (median 65 years) after an average of 38.3 years (median 38 years) of follow up.

The distribution of the cumulative external radiation dose with no lag is given in Table 3. Because this operation was shut down in 1966 and follow up was through 1993, lagging the doses had little effect on the cumulative external radiation dose. The mean cumulative whole body exposure was 47.8 mSv (median 15.3 mSv) resulting in a population dose of 120,063 mSv.

Results of the SMR analyses for the total cohort are presented in Tables 4 and 5 for selected nonmalignant and cancer causes. The SMR for all causes of 0.92 (95% Confidence Interval [CI] 0.86-0.97) was significantly below 1.00. Significant mortality deficits were also observed for circulatory system diseases (SMR=0.88, 95 percent CI 0.80-0.96) and accidents (SMR=0.76, 95 percent CI 0.60,0.95). Fewer deaths than expected were observed for respiratory system diseases (SMR=0.84, 95 percent CI 0.66,1.09) and digestive system diseases (SMR= 0.82, 95 percent CI 0.60-1.0).

Of the 1,056 deaths observed, 297 (28 percent) were due to cancer. The SMR for all cancers was 1.10 (95 percent CI 0.98-1.23) with many of the site-specific SMRs elevated. Among the organ systems of particular interest, cancers sites with at least a 30 percent excess over expected were esophagus (SMR=1.40, 95 percent CI 0.63-2.71), rectum (SMR=1.45, 95 percent CI 0.96, 2.59), pancreas (SMR=1.31, 95 percent 0.78-2.09), larynx (SMR=1.36, 95 percent CI 0.86-3.18), kidney (SMR=1.34, 95 percent CI 0.65-2.42), and multiple myeloma (SMR=1.33, 95 percent CI 0.43-3.10). Among the nonmalignant outcomes of interest, only chronic nephritis (SMR=2.18, 95 percent CI 0.93-4.21) exhibited such an excess. The SMRs for those employed in a Mallinckrodt division other than the Uranium Division were not different from those for workers only worked at Mallinckrodt in the Uranium Division.

Results of the trend tests for cumulative whole body exposure are shown in Table 6 which includes cancers mentioned on the death certificate but not as the underlying cause of death. Repeating this analysis excluding deaths where the cancer was not the underlying cause produced similar results. Among the nonmalignant outcomes of interest, no trend was found with increasing dose. For cancer sites, only kidney cancer demonstrated a statistically significant trend with increasing dose (one-tailed p value =0.02). Among outcomes used as indirect measures of the possible differences in smoking and alcohol consumption between the dose groups, there was no evidence of a relationship: circulatory disease (one-tailed p value=0.26), smoking-related cancers (one-tailed p value=0.83), non-acute respiratory disease (one-tailed p value=0.69), and liver cirrhosis (one-tailed p value=0.94).

The conclusions derived from the results of modeling the dose-response relationship for excess relative risk were the same as the trend test. Only kidney cancer showed a significant relationship with radiation dose with an excess relative risk of 12.9 per Sv, which is equivalent to a 12.9% increase per 10 mSv of whole body exposure. The 90 percent confidence interval was (1.4-67.6).

DISCUSSION

A number of studies of nuclear workers have been done investigating the relationship between mortality and occupational exposure to external ionizing radiation (5-10). The study by Fry, et al (10) of nuclear workers who received 50 mSv or more of external ionizing radiation in a calendar year includes over 100 of the workers in the current study. All of these studies have a mean cumulative whole body radiation exposure of the same order of magnitude and a length of follow up similar to the current study. Like the current study, the all causes SMR was significantly reduced indicating the presence of the healthy worker effect. In each case, the all cancer SMR was slightly greater than the all causes SMR but greater than expected in only two of the other studies (8, 10). In general, the site-specific cancer SMRs have been less than expected. The only significantly increased SMRs reported were for lung cancer (8) and thyroid cancer (7). The only significant positive dose-response trends were for lung cancer (5), melanoma and other skin cancers (7), multiple myeloma (6) and leukemia (6,7). Collectively, these studies reported elevated SMRs for 11 additional site-specific cancers included in the current study: esophagus (5, 10), colon (10), rectum (10), larynx (5, 10), prostate (10), testis (6, 7), bladder (8, 10), kidney (5, 7-10), brain (8, 10), lymphosarcoma (10), and leukemia (9). Thyroid cancer was the only site with fewer observed deaths than expected in the current study.

In the study, the SMR for all cancers was 1.10 with the lower bound on the 95 percent CI almost reaching statistical significance. This increase in the SMR was not due to any particular cancer site but rather resulted from an increase in the SMR for 13 of the 21 site-specific cancers.

The only statistically significant dose-response relationship was found between kidney cancer and external ionizing radiation. Because of the many outcomes that were evaluated, this result may have occurred by chance alone. However, a relationship between kidney cancer and external radiation exposure has been reported in a number of other studies. The SMR for kidney cancer was never decreased in any of the nuclear worker studies cited earlier (5, 7-10). The average cumulative external radiation dose among the monitored workers in these studies ranged from 7.8 mSv (5) to 56.5 mSv (7) which is similar to the mean of 47.8 mSv in the current study. However, of the four studies that investigated a dose-response relationship (5-7, 9), only one found this relationship to be positive (9). A positive relationship between external ionizing radiation and kidney cancer has been reported for patients treated with ionizing radiation for ankylosing spondylitis and cervical cancer (12, 13). Darby (12) found a relative risk for kidney cancer of 1.52 among ankylosing spondylitis patients who had an average dose of 1 Sv and were treated five or more years earlier with a single course of X rays. In a study of women treated with radiation for cervical cancer, Boice, et al. (13) reported a kidney cancer relative risk of 1.23 which increased to 3.50 among 15 year survivors. The estimated kidney dose was 2 Sv. While the average dose was much greater in these two studies than the current one, the excess relative risk of 71 per Sv reported by Boice falls within the 90 percent confidence interval observed here. Table 7 presents selected characteristics of these 11 cases. A number of risk factors have been identified for kidney cancer. Among them are smoking, the use of phenacetin or diuretics, obesity, high protein intake, asbestos exposure, and ionizing radiation (11). Information about most of these factors was not available for the cases. Two cases held jobs in the Uranium Division in which asbestos exposure was possible; one was a pipe coverer (case 4) the other a pipefitter (case 11). Although smoking information was not available for any of the cases, there was no indication of a relationship between smoking and radiation exposure in the study population using indirect methods.

From 1946 through mid 1955, pitchblende ore was processed in the Uranium Division. The pitchblende required an extra processing step to remove the radium and other impurities. Prior to removal of the radium, potential for external radiation exposure was high. Most of the operations were done by manual batch methods over the period of pitchblende processing, and the plant in which the processing was done became increasingly contaminated with radium over time. Even after pitchblende processing ended, residual radium contamination increased the potential for external radiation exposure. Nine of the workers with kidney cancer, worked in the plant where pitchblende was processed during the time when it was processed. Five of these nine workers had jobs processing the uranium prior to removal of the radium. All but one of the five workers were the most highly exposed kidney cancer cases. The period of employment and the work history of the cases strengthens the belief in the statistical relationships.

However, processing of uranium also produces a potential chemical and internal radiation exposure hazard. Neither of these hazards was considered here. Since inhalation of dust was the primary route for internal deposition, the kidney is one of the major sites of deposition for uranium transported from the lung. This raises the possibility that internal exposure, both chemical and radiological, may be responsible for the association seen between kidney cancer and external radiation exposure. The increased SMR for chronic nephritis strengthens this possibility.

There were a number of other weaknesses in this study. These include the small size of the cohort, the possible bias in assignment of person years resulting from unidentified deaths, incomplete personal monitoring records on external radiation exposure for all workers, and the failure to consider chemical exposures resulting from the uranium processing operations. Unidentified deaths among the cohort members could have resulted because of the 45 workers lost to follow up before 1979 and the assumption that workers not known to be alive at the end of 1978 and not identified as deceased by NDI were assumed alive through the end of the study. Accumulation of person years for the 45 workers lost to follow up prior to 1979 was terminated on the date they were last known alive. The number of missed deaths resulting from the NDI assumptions based on a study by Calle and Terrill (14) was likely to be small. They found the sensitivity to be 98% and specificity to be 99.9% among persons with known vital status and a known social security number. Because a small number of workers were involved, any bias in assignment of person years was minimal. Personal external radiation monitoring data was missing for 20.8 percent of the total 16,573 employment years of the cohort. Over a third of the years with missing data occurred before 1946; the personal monitoring program began in mid 1945. Since processing methods remained fairly consistent from 1942 through 1946, using 1946 data to fill in the missing years should provide valid exposure estimates for this early period. In addition to uranium, potential chemical hazards resulting from the processing operations include nitric acid and nitrous vapors, hydrofluoric acid and fluorides, sulfuric acid, silica, tributyl phosphate, hexane and ether. None of these materials is a known carcinogen.

Despite the limitations of this study, the unique exposure to pitchblende resulting in high external radiation dose exposure and the long length of follow up were additional reasons for doing this cohort study. With over 90 percent of the cohort followed at least 20 years, enough time had elapsed for the development of cancers that may have resulted from occupational radiation exposure. The significant dose-response relationship between external radiation exposure and kidney cancer is validated by the job histories of the cases. However, this association can only be considered provisional until further study includes the investigation of the relationship with internal radiation dose. Work is currently underway to reconstruct annual internal radiation lung doses resulting from inhaled uranium from contemporary personal and area monitoring data, as well as, to evaluate the internal dose resulting from radium contained in and radon emitted from the pitchblende ore. When the dose reconstruction is complete, the relationship between internal radiation dose and selected disease outcomes will be examined. Suggestions for additional study include the pooling of this cohort with the worker populations of other uranium processing facilities, especially the one at Fernald, Ohio. Mallinckrodt was instrumental in the design of the process operations as well as health and safety programs at Fernald. Since these two populations represent the majority of workers employed in the DOE uranium processing operations, doing a pooled study which considers both internal and external radiation exposures could increase the power to detect any health effects.

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TABLE 1. Reasons for exclusion of workers from the Mallinckrodt Chemical Workers Uranium Division cohort

Total ever employed in the Uranium Division	3,259
Exclusions-	
Females	556
Non-white males	43
Unknown race/gender	82
Birth date errors	5
Work history error	59
Study Populations	2,514

Table 2. Statistics for selected characteristics of the Mallinckrodt Chemical Workers cohort

Characteristic	Mean	Median	Range
Age at hire	30.3	28	16, 66
Year of hire	1951.6	1951	1942, 1966
Years employed	5.2	3	<1, 25
Length of follow up	34.6	36	0, 51

TABLE 3. Cumulative external radiation dose (mSv) distribution with no lagging for the 2,514 white male workers employed for at least 30 days at the Mallinckrodt Chemical Works Uranium Division

Dose*	**No. of Workers**	**Percent**
<5	770	30.6
5-	289	11.5
10-	347	13.8
20-	373	14.8
40-	334	13.3
80-	208	8.3
160+	193	7.7
Total	2514	100.0

* Mean = 47.8; Median = 15.3; Range = 0-1099.7 Total = 120,063

Table 4. Standardized mortality ratios (SMR) for selected causes of death adjusted for age and calendar period, 1942-1993

Cause of Death	Observed	SMR	95% C.I.
ALL CAUSES (000-999)	1,056	0.92	0.86,0.97
INFECTIVE AND PARASITIC DISEASE (000-139)	11	0.77	0.40,1.31
Tuberculosis (010-019)	5	0.90	0.32,1.94
ALL CANCERS (140-209)	297	1.10	0.98,1.23
BENIGN NEOPLASMS (210-239)	2	0.66	0.08,2.05
ENDOCRINE, NUTRITIONAL, AND METABOLIC DISEASES (240-279)	13	0.64	0.34,1.10
Diabetes mellitus (250)	9	0.55	0.27,0.99
DISEASES OF THE BLOOD AND BLOOD-FORMING ORGANS (280-289)	2	0.75	0.09,2.31
MENTAL DISORDERS (290-317)	5	0.70	0.23,1.63
DISEASES OF THE NERVOUS SYSTEM AND SENSE ORGANS (320-389)	12	0.93	0.50,1.55
DISEASES OF THE CIRCULATORY SYSTEM (390-458)	492	0.88	0.80,0.96
Chronic rheumatic heart disease (393-398)	8	1.00	0.46,1.85
Ischemic heart disease (410-414)	350	0.88	0.79,0.98
Cerebrovascular disease (430-438)	53	0.85	0.64,1.09
DISEASES OF THE RESPIRATORY SYSTEM (460-519)	68	0.84	0.66,1.06
Pneumonia (480-486)	29	1.11	0.75,1.56
Emphysema (492)	9	0.65	0.31,1.17
Asthma (493)	0		
DISEASES OF THE DIGESTIVE SYSTEM (520-577)	44	0.82	0.60,1.09
Ulcer of stomach, duodenum, peptic ulcer, site unspecified (531-533)	3	0.50	0.13,1.31
Cirrhosis of liver (571)	22	0.79	0.50,1.17
DISEASES OF GENITOURINARY SYSTEM (580-629)	15	0.99	0.56,1.57
Chronic nephritis (582)	7	2.18	0.93,4.21
DISEASES OF THE SKIN AND SUBCUTANEOUS TISSUE (680-709)	3	3.13	0.78,8.10
DISEASES OF THE MUSCULOSKELETAL SYSTEM AND CONNECTIVE TISSUE (710-738)	1	0.49	0.01,2.16
SYMPTOMS AND ILL-DEFINED CONDITIONS (780-799)	18	1.44	0.85,2.28
ACCIDENTS, POISONINGS, AND VIOLENCE (NATURE OF INJURY) (E800-E998)	71	0.76	0.60,0.95
All accidents (E800-E949)	47	0.76	0.56,1.00
Motor vehicle traffic accidents (E810-E827)	20	0.71	0.44,1.07

Cause of Death	Observed	SMR	95% C.I.
Suicide and self-inflicted injury (E950-E959)	19	0.82	0.50,1.24

Table 5. Standardized mortality ratios (SMR) for selected cancer sites adjusted for age and calendar period, 1942-1993

Cause of Death	Observed	SMR	95% C.I.
ALL CANCERS (140-209)	297	1.10	0.98,1.23
Malignant neoplasm of buccal cavity and pharynx (140-149)	7	0.94	0.41,1.82
Malignant neoplasm of digestive organs and peritoneum (150-159)	73	1.06	0.83,1.32
Esophagus (150)	9	1.40	0.63,2.71
Stomach (151)	5	0.47	0.17,1.01
Colon (153)	29	1.16	0.79,1.64
Rectum (154)	9	1.45	0.69,2.59
Liver (155-156)	2	0.43	0.05,1.34
Pancreas (157)	18	1.31	0.78,2.09
Malignant neoplasm of respiratory system (160-163)	106	1.06	0.87,1.27
Larynx (161)	5	1.36	0.44,3.18
Lung (162)	100	1.05	0.86,1.27
Malignant neoplasm of bone (170)	1	1.21	0.03,5.32
Malignant neoplasm of skin (172-173)	4	0.79	0.24,1.83
Malignant neoplasm of prostate (185)	24	1.25	0.81,1.82
Malignant neoplasm of testis (186-187)	1	0.91	0.23,4.03
Malignant neoplasm of bladder (188)	8	1.13	0.47,1.95
Malignant neoplasm of kidney (189)	9	1.34	0.65,2.42
Malignant neoplasm of eye (190)	0		
Malignant neoplasm of brain (191-192)	12	1.60	0.86,2.68
Thyroid (193)	0		
Neoplasms of lymphatic and hematopoietic tissue (200-209)	28	1.11	0.75,1.57
Lymphosarcoma (200)	1	0.25	0.01,1.39
Hodgkin's disease (201)	2	0.90	0.11,2.77
Multiple myeloma (203)	5	1.33	0.43,3.10
Leukemia (204-207)	12	1.21	0.65,2.03
Other lymphoid tissue (202-203)	10	1.16	0.56,2.13

Table 6. Relation of mortality from selected causes of death to cumulative whole body exposure adjusted for age, calendar period, and Main Plant status (doses are lagged by 2 years for leukemia, and 10 years for other causes of death)

	Cumulative Whole Body Exposure (mSv)								
	0 -	5 -	10 -	20 -	40 -	80 -	160 -	Total	
Person Years	42,937	7,552	9,241	9,316	8,203	5,561	4,947	87,757	
Mean Dose (weighted by person-years)	**0.83**	**7.20**	**14.62**	**28.48**	**57.89**	**110.78**	**297.80**		
Cause of Death	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**Total Deaths**	**P Value of Trend Test**
All causes (000-999)	288/302.22	112/101.64	120/120.92	148/139.18	157/169.21	112/105.86	119/110.96	1,056	0.44
All cancers (140-209)	92/85.63	31/32.06	32/41.81	50/45.98	52/53.87	36/34.12	36/35.53	329	0.93
All cancers except leukemia (140-203)	89/81.10	28/30.74	31/40.13	47/44.59	52/52.32	34/33.33	36/34.80	317	0.85
Esophagus (150)	0/2.48	1/1.06	0/1.03	3/1.05	4/1.66	0/0.82	1/0.89	9	0.65
Stomach (151)	2/1.94	0/0.30	0/0.55	1/0.48	2/0.77	0/0.48	0/0.49	5	0.51
Colon (153)	6/6.63	5/2.73	6/3.75	6/4.57	1/5.73	4/3.75	3/3.84	31	0.41
Rectum (154)	3/3.23	2/0.95	0/1.20	2/1.35	2/1.47	0/0.80	1/1.01	10	0.83
Pancreas (157)	6/4.53	1/1.96	2/2.47	1/2.59	1/2.78	3/1.87	4/1.80	18	0.16
Lung (162)	41/29.02	10/11.27	8/14.67	15/16.21	15/18.05	13/11.36	10/11.42	112	0.66
Prostate (185)	8/7.48	4/2.76	4/2.82	0/3.70	6/5.25	4/3.09	3/3.90	29	0.69
Bladder (188)	1/1.60	0/0.71	1/1.31	4/1.40	1/1.19	0/0.90	1/0.90	8	0.68
Kidney (189)	3/2.54	0/1.04	0/1.48	2/1.59	1/1.66	1/1.39	4/1.30	11	0.02
Brain (191-192)	4/3.22	2/1.19	0/1.66	2/2.16	3/1.98	0/1.35	2/1.43	13	0.77
Multiple myeloma (203)	1/1.33	0/0.56	1/0.76	1/0.68	1/0.57	1/0.53	0/0.57	5	0.68
All leukemia (204-207)	3/4.05	3/1.34	1/2.79	2/1.55	0/0.71	3/0.81	0/0.75	12	0.74
All leukemia except chronic lymphocytic leukemia	3/3.81	3/1.25	1/1.60	1/1.39	0/1.58	3/0.70	0/0.67	11	0.79
All lymphopoietic (200-209)	6/9.02	3/3.02	3/4.54	6/4.05	6/4.52	4/2.93	3/2.91	31	0.70

	Cumulative Whole Body Exposure (mSv)								
	0 -	5 -	10 -	20 -	40 -	80 -	160 -	Total	
Smoking-related cancers (140-150, 161, 162, 157, 188, 189.1)	50/41.12	13/16.27	11/21.06	26/22.85	23/25.91	20/16.42	17/16.38	160	0.83
Non smoking-related cancers	42/44.52	18/15.79	21/20.75	24/23.13	29/27.96	16/17.70	19/19.15	169	0.94
Cause of Death	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**O/E**	**Total Deaths**	**P Value of Trend Test**
Non-cancer causes (not 140-209)	196/216.59	81/69.59	88/85.11	98/93.20	105/115.35	76/71.74	83/75.43	727	0.39
Circulatory system (390-458)	106/125.71	52/45.53	55/56.29	72/62.89	72/78.96	53/49.37	59/50.26	469	0.26
Acute respiratory diseases (460-489)	8/8.86	3/3.19	2/3.22	4/3.74	5/5.29	4/2.87	5/3.82	31	0.42
Non-acute respiratory diseases (490-519)	10/8.32	5/3.37	3/4.88	7/5.40	4/6.87	2/3.83	6/4.40	37	0.69
Emphysema (492)	4/2.18	1/0.84	2/1.18	0/1.00	1/2.00	0/0.79	1/1.03	9	0.60
Digestive diseases (520-629)	19/14.94	3/4.35	4/5.10	3/5.07	4/5.10	6/4.25	5/4.30	44	0.50
Liver cirrhosis (571)	9/7.42	2/2.08	3/2.73	1/2.78	1/2.67	4/2.19	2/2.14	22	0.94
Genitourinary system diseases (580-629)	3/4.13	1/1.96	1/1.54	3/1.50	3/2.13	2/1.36	2/2.37	15	0.92
Chronic nephritis (582)	0/1.57	1/0.59	0/0.96	2/1.00	2/1.16	1/0.89	1/0.82	7	0.49

Table 7. Characteristics of Mallinckrodt workers who had kidney cancer listed on their death certificate

Case	Year of Birth	Year of Hire	Years Employed	Year of Death	Worked During Pitchblende Processing	Worked at Mallinkrodt Outside Uranium Processing	Total External Radiation Dose (mSv)
1	1919	1944	0	1993	No	No	4.9
2	1912	1945	20	1987	Yes*	No	436.0
3	1920	1946	6	1993	Yes	No	90.2
4	1915	1947	10	1991	Yes*	No	185.2
5	1923	1947	11	1984	Yes*	Yes	480.0
6	1915	1948	10	1983	Yes*	No	259.0
7	1912	1951	7	1985	Yes*	No	36.9
8	1921	1953	6	1969	Yes	Yes	43.1
9	1923	1956	9	1981	Yes*	No	25.5
10	1933	1959	2	1981	No	No	3.7
11	1922	1960	1	1988	No	No	2.2

* The employee's work history documents working with pitchblende ore prior to removal of the radium daughter products.