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Mortality among United States radiologic technologists, 1926-90

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The possible mortality risk from low level chronic exposures to ionizing radiation was evaluated among 143,517 United States radiologic technologists certified by the American Registry of Radiologic Technologists between 1926-80. This is one of the few occupational studies of primarily women (73 percent) exposed to radiation during their employment. More than 2.8 million person-years of follow-up were accrued through 1990, and 7,345 deaths were identified. A strong healthy-worker effect was observed (standardized mortality ratios [SMR] for all causes and all cancers were 0.69 and 0.79, respectively). Lung cancer (429 deaths) was not increased with available measures of radiation exposure and no significant associations were observed for acute, myelogenous, and monocytic leukemia (74 deaths). Relative to the general population, the standardized mortality ratio (SMR) for female breast cancer was 0.99 (based on 425 deaths); however, breast cancer was significantly elevated relative to all other cancers in a test of homogeneity of SMRs (ratio of SMRs = 1.3, *P* < 0.0001). Significant risks were correlated with employment before 1940 (SMR = 1.5; 95 percent confidence interval [CI] = 1.2-1.9), when radiation doses were likely highest, and among women certified for more than 30 years (SMR = 1.4, CI = 1.2-1.7) for whom the cumulative exposure was likely greatest. Using an internal referent group, risk increased with duration of certification among the 1,890 women certified before 1940 (*P*-trend < 0.001). While the findings for breast cancer are consistent with a radiation effect, possible misclassification in exposure (based on number of years certified) and potential confounding associated with reproductive histories preclude a causal conclusion. *Cancer Causes and Control* 1998, 9, 67-75

Key words: Mortality, neoplasms (radiation-induced), occupational diseases, radiologic technicians, United States.

Introduction

Experimental studies consistently find that fractionated low doses of radiation produce fewer tumors than single exposures of the same total dose. This appears to be related, in part, to the ability of cells to repair radiation damage when exposures and exposure rates are sufficiently low.[1,2] A study of United States Army radiation technologists[3] failed to find a cancer risk, but numbers of cases were small. Other studies of radiologists and medical radiation workers have indicated that fractionated doses accumulating to presumably high levels are capable of inducing leukemia[4-8] and skin cancer[6,8] in humans. Based on a small number of cases (n = 20),[8] breast cancer was elevated among female Chinese radiation technologists who apparently were exposed to relatively high levels of radiation (> 1 Sv, estimated).

Occupational studies of workers in the nuclear indus-

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try in the US have not identified a leukemia risk,[9] despite a range of doses. Analyses of a combined international series from the US, United Kingdom, and Canada (85 percent male)[10] report a dose-response relationship for leukemia, but not for solid tumors. Confidence intervals were wide and both findings were compatible with risks predicted from studies of acute exposures among the atomic bomb survivors.

Except for the Chinese series, prior cohorts of medical radiation workers have been comprised primarily of exposed male workers. To provide additional information on the possible risk associated with long-term low-level radiation exposure, a cohort of US radiologic technologists certified by the American Registry of Radiologic Technologists (ARRT) between 1926 and 1982 was identified. A complete description of the population and study design was provided earlier.[11] This cohort is predominantly female (73 percent), offering an unique opportunity to evaluate risk of breast and other cancers linked with exposure to ionizing radiation among women. In previous nested case-control analyses of 528 female technologists who reported breast cancer on a comprehensive mail questionnaire,[12,13] no association was found with any measure of radiation exposure, including number of years worked, number of years certified, recorded dosimetry dose, occupational practice (radiotherapy, fluoroscopy), or personal X-ray exposures. In the current report, the complete mortality experience of this cohort is presented with special emphasis on deaths due to leukemia and breast cancer for which excess risks have been linked to relatively low-level radiation exposures.

Materials and methods

A collaborative study was initiated in 1982 between the ARRT, the University of Minnesota, and the US National Cancer Institute to evaluate health outcomes associated with long-term occupational exposure to radiation. A brief description of the study population and methods is presented below.

Study population

The ARRT, which has been in existence since 1926, certifies technologists throughout the US in radiography, nuclear medicine, and radiation therapy. Through 1982, there were 143,517 registrants who were certified for at least two years and resided in the US. Technologists certified after 1980 or for less than two years were excluded. Information for individual technologists was obtained from the computerized files of the ARRT, and included name, date of birth, gender, last known address, date certified, professional specialty, and date certification was dropped (if applicable).

Tracing

For active members, a current address was available from the ARRT. For inactive registrants, tracing efforts included the use of Post Office address-correction requests, telephone and other directories, credit reports, motor vehicle bureau records, Social Security Administration mortality files, Health Care Financing Administration records, the National Death Index, and state mortality tapes. Study subjects were also linked with Internal Revenue Service records through a cooperative agreement with the National Institute for Occupational Safety and Health (NIOSH). Death certificates were obtained for decedents and causes of death were coded according to ICD-8.[14]

Statistical procedures

Since eligibility for the study included a minimum certification period of two years, person-years of observation did not begin to accrue for individuals until two years after their date of certification. Follow-up ended with the date of death, date of last known vital status, or 1 January 1991, whichever was earlier. Numbers of expected deaths were calculated for age-, gender-, and calendar time-specific categories using US mortality rates.[15] Standardized mortality ratios (SMR) were computed as the number of observed deaths divided by the number of expected deaths. Exact methods were used to calculate 95 percent confidence intervals (CI).[16] Two-sided *P*-values were used for all hypothesis tests. Tests of homogeneity were also conducted to evaluate whether there were significant differences in mortality from selected causes relative to other causes, *e.g.*, breast cancer compared with all other cancers.[17]

Additional analyses to evaluate patterns of risk for breast cancer and leukemia (by sub-type) were conducted using an internal referent group to minimize the potential for confounding related to differences in the worker and general populations. For computing relative risks, data were cross-classified by attained age group, calendar year, year first certified, gender, and number of years certified. For each cell of the cross-classification, the number of observed deaths and the person-years were computed using the DATAB program.[18] A lag interval of 10 years was used for computing number of years certified for the breast cancer analyses; no lag interval was used for leukemia. Maximum likelihood estimates of relative risks (RR) and CIs were computed using the AMFIT program for fitting Poisson regression models.[18] RRs were adjusted for attained age, calendar year of follow-up, and gender.

Results

Vital status was determined for 99.2 percent of cohort members as of 31 December 1990: 7,306 technologists

Table 1. Demographic characteristics of 143,429[a] radiologic technologists, by gender

Characteristic	Females (*n* = 105,319) Number	Males (*n* = 38,110) Number
Birth year		
< 1930	11,535	6,096
1930-39	13,804	5,973
1940-49	33,110	12,768
1950-59	45,942	13,198
1960+	928	75
Year certified		
1926-39	1,890	385
1940-49	4,093	1,485
1950-59	13,520	5,230
1960-69	30,368	10,009
1970-79	49,949	19,126
1980+	5,499	1,875
Age at certification (yrs)		
< 20	10,327	1,037
20-24	76,691	20,217
25-29	8,647	10,358
30-39	6,900	5,027
40+	2,754	1,471
No. of persons starting follow-up interval (yrs)		
2	105,319	38,110
5	105,090	37,958
10	104,649	37,673
20	51,523	17,107
30	20,064	6,857
40	5,033	1,474

[a] 88 technologists were excluded from analysis due to missing dates of birth and/or certification.

(5.1 percent) were confirmed deceased; 39 (< 0.1 percent) were presumed deceased; 134,934 (94.1 percent) were confirmed alive; and 1,150 (0.8 percent) were lost to follow-up. Table 1 presents characteristics of the study population. Most of the eligible radiologic technologists were born between 1940 and 1959 (73 percent), and became certified between 1960 and 1979 (76 percent). Approximately 80 percent of male and female technologists were first certified in their 20s, mainly between the ages of 20 and 24 years. More than 2.8 million person-years of observation were accumulated. The average length of follow-up was 19.8 years, with 48 percent of technologists contributing 20 or more person-years.

Overall, mortality among the technologists was 31 percent lower than expected based on general population rates (Table 2). Statistically significant deficits in risk were observed for mortality from: all malignant neoplasms; cancers of the buccal cavity and pharynx, stomach, colon, larynx, lung, skin, and cervix; endocrine, nutritional, and metabolic diseases; mental disorders; diseases of the nervous system and sense organs; diseases of the circulatory system; diseases of the respiratory system; diseases of the digestive system; diseases of the genitourinary system; and accidents, poisonings, and violence. Mortality patterns were generally similar for male and female technologists.

Although breast cancer and leukemia did not differ from unity in relation to general population rates, a test of homogeneity revealed that the SMR for breast cancer was significantly higher than the SMR for all other cancers (ratio of SMRs = 1.3, $P < 0.0001$). The SMR for leukemia was 20 percent greater than the SMR for non-leukemia malignancies (ratio of SMRs = 1.2, $P = 0.09$). Lung cancer was not increased relative to other cancers (ratio of SMRs = 0.9, $P = 0.13$).

Table 3 presents SMRs for death from all causes and selected malignant neoplasms by the number of years a technologist was certified. Risk of breast cancer increased significantly with length of certification ($P < 0.0001$); technologists certified less than 10 years were at significantly low risk (SMR = 0.7, CI = 0.5-0.9) while those certified for 30 or more years had a significantly increased risk (SMR = 1.4, CI = 1.2-1.7). Mortality risks for leukemia and lung cancer were not related to length of certification. Risks for other cancers did not rise with increasing number of years of certification (data not shown).

In general, all-cause mortality and all-cancer mortality declined with more recent calendar period of first certification (Table 4). Breast cancer was increased significantly among women first certified before 1940 (SMR = 1.5, CI = 1.2-1.9), but the risks declined significantly among technologists first registered in more recent calendar-year periods (P-trend < 0.0001). Breast cancer was decreased significantly among women certified after 1960 (SMR = 0.8, CI = 0.7-1.0). Lung cancer and leukemia mortality did not demonstrate a consistently declining risk with certification in the later calendar periods. Patterns in risk for other cancers did not differ by calendar period of certification (data not shown).

Using Poisson regression techniques, we found risk of mortality from breast cancer to be associated significantly with length of certification among technologists certified before 1940 ($P < 0.001$), but not among technologists certified in 1940 or later (Table 5). Our data suggest a decline in breast cancer risk with more recent calendar period of first certification within each of the number of years certified categories; however, none of the trends was significant statistically. As shown in Table 6, duration of certification was not related to acute, myelogenous, and monocytic leukemia or to chronic lymphatic leukemia (CLL) within any calendar period of first certification. Within each category of number of years certified, risks

Table 2. Observed cause-specific deaths among radiologic technologists and standardized mortality ratios[a] (SMR), by gender

Cause of death (ICD-8)[14]		Male	Female	Total	(CI)
	Persons	38,110	105,319	143,429	
	Person-years	737,289	2,102,176	2,839,466	
All causes (000-999)	Observed	2,913	4,432	7,345	
	SMR	0.68[b]	0.70[b]	0.69[b]	(0.68-0.71)
Infective & parasitic diseases (000-136)	Observed	100	56	156	
	SMR	1.21	0.60[b]	0.89	(0.75-1.04)
All malignant neoplasms (140-209)	Observed	641	1,517	2,158	
	SMR	0.70[b]	0.84[b]	0.79[b]	(0.76-0.83)
Buccal cavity & pharynx (140-149)	Observed	17	14	31	
	SMR	0.68	0.66	0.67[b]	(0.45-0.95)
Esophagus (150)	Observed	11	12	23	
	SMR	0.51[b]	0.96	0.67	(0.43-1.01)
Stomach (151)	Observed	21	32	53	
	SMR	0.62[b]	0.71	0.67[b]	(0.50-0.88)
Colon (153)	Observed	59	132	191	
	SMR	0.74[b]	0.80[b]	0.78[b]	(0.67-0.90)
Rectum (154)	Observed	17	23	40	
	SMR	0.89	0.72	0.78	(0.56-1.06)
Liver, gallbladder, bile ducts (155-156)	Observed	11	24	35	
	SMR	0.74	0.73	0.73	(0.51-1.02)
Pancreas (157)	Observed	36	59	95	
	SMR	0.81	0.85	0.83	(0.67-1.02)
Larynx (161)	Observed	6	2	8	
	SMR	0.52	0.42	0.49[b]	(0.21-0.96)
Lung, trachea, bronchus (162)	Observed	203	226	429	
	SMR	0.65[b]	0.86[b]	0.74[b]	(0.67-0.82)
Bone (170)	Observed	2	2	4	
	SMR	0.54	0.31	0.39	(0.11-1.01)
Skin, including melanoma (172-173)	Observed	18	23	41	
	SMR	0.64	0.60[b]	0.62[b]	(0.44-0.84)
Breast (174)	Observed	2	425	427	
	SMR	1.76	0.99	0.99	(0.90-1.09)
Cervix (180)	Observed	—	21	21	
	SMR	—	0.27[b]	0.27[b]	(0.16-0.39)
Uterus (181-182)	Observed	—	40	40	
	SMR	—	0.87	0.87	(0.59-1.13)
Other female genital (183-184)	Observed	—	105	105	
	SMR	—	0.85	0.85	(0.69-1.02)
Prostate (185)	Observed	39	—	39	
	SMR	0.79	—	0.79	(0.56-1.08)
Testis, other & unspecified male genital (186-187)	Observed	3	—	3	
	SMR	0.39	—	0.39	(0.08-1.15)
Bladder (188)	Observed	16	17	33	
	SMR	0.82	1.03	0.91	(0.63-1.28)
Kidney, other & unspecified urinary organs (189)	Observed	24	25	49	
	SMR	1.00	0.93	0.96	(0.71-1.27)
Eye (190)	Observed	1	0	1	
	SMR	1.54	0.00	0.51	(0.01-2.78)
Brain and other CNS (191-192)	Observed	23	53	76	
	SMR	0.65[b]	0.94	0.83	(0.65-1.03)
Thyroid (193)	Observed	0	4	4	
	SMR	0.00	0.81	0.60	(0.16-1.50)
Lymphosarcoma & reticulum cell sarcoma (200)	Observed	17	22	39	
	SMR	1.17	0.94	1.03	(0.72-1.38)
Hodgkin's disease (201)	Observed	7	21	28	
	SMR	0.57	1.06	0.87	(0.58-1.26)

Cont.

Table 2. Continued

Cause of death (ICD-8)[14]		**Male**	**Female**	**Total**	**(CI)**
Multiple myeloma (203)	Observed	12	11	23	
	SMR	1.00	0.55[b]	0.71	(0.45-1.06)
Leukemia (204-207)	Observed	37	66	103	
	SMR	0.92	0.94	0.93	(0.76-1.13)
Benign & unspecified neoplasms (210-239)	Observed	9	24	33	
	SMR	0.77	0.82	0.81	(0.56-1.13)
Endocrine, nutritional, metabolic diseases (240-279)	Observed	84	79	163	
	SMR	1.00	0.44[b]	0.62[b]	(0.52-0.71)
Diseases of blood & blood-forming organs (280-289)	Observed	10	18	28	
	SMR	1.06	0.78	0.86	(0.57-1.24)
Mental disorders (290-315)	Observed	16	38	54	
	SMR	0.39[b]	0.92	0.66[b]	(0.49-0.85)
Diseases of nervous system & sense organs (320-389)	Observed	22	70	92	
	SMR	0.42[b]	0.69[b]	0.60[b]	(0.48-0.73)
Diseases of circulatory system (390-458)	Observed	1,218	1,544	2,762	
	SMR	0.70[b]	0.65[b]	0.67[b]	(0.65-0.70)
Diseases of respiratory system (460-519)	Observed	163	205	368	
	SMR	0.69[b]	0.62[b]	0.65[b]	(0.58-0.72)
Diseases of digestive system (520-577)	Observed	134	163	297	
	SMR	0.62[b]	0.57[b]	0.59[b]	(0.53-0.66)
Diseases of genitourinary system (580-629)	Observed	34	66	100	
	SMR	0.73	0.63[b]	0.66[b]	(0.54-0.81)
Diseases of skin & subcutaneous tissue (680-709)	Observed	1	7	8	
	SMR	0.33	0.71	0.62	(0.27-1.22)
Diseases of musculoskeletal system (710-738)	Observed	8	26	34	
	SMR	1.08	0.79	0.85	(0.59-1.18)
Accidents, poisonings, violence (800-998)	Observed	388	415	803	
	SMR	0.52[b]	0.62[b]	0.57[b]	(0.53-0.61)

[a] Number of observed deaths divided by number of expected deaths based on US population rates.
[b] $P < 0.05$.

Table 3. Observed deaths from selected causes among radiologic technologists, expected deaths based on US mortality, and standardized mortality ratios[a] (SMR), by number of years certified

Cause of death		**Number of years certified**				***P*-trend**
		< 10	**10-19**	**20-29**	**30+**	
	Persons	143,429	132,948	57,570	17,758	
	Person-years	1,259,228	1,047,604	414,104	118,530	
All causes	Observed	1,343	1,998	2,269	1,735	
	Expected	2,260.0	3,094.8	2,952.7	2,278.3	
	SMR	0.6[c]	0.7[c]	0.8[c]	0.8[c]	< 0.0001
All malignant neoplasms	Observed	310	556	742	550	
	Expected	458.7	791.7	867.6	610.6	
	SMR	0.7[c]	0.7[c]	0.9[c]	0.9[c]	< 0.0001
Lung	Observed	53	102	155	119	
	Expected	73.0	147.5	203.8	153.3	
	SMR	0.7[c]	0.7[c]	0.8[c]	0.8[c]	0.46
Breast[b]	Observed	47	119	150	109	
	Expected	66.4	142.3	144.3	77.6	
	SMR	0.7[c]	0.8	1.0	1.4[c]	< 0.0001
Leukemia	Observed	29	20	30	24	
	Expected	29.4	34.5	27.8	18.9	
	SMR	1.0	0.6[c]	1.1	1.3	0.19

[a] Number of observed deaths divided by number of expected deaths.
[b] Female technologists only.
[c] $P < 0.05$.

Table 4. Observed deaths from selected causes among radiologic technologists, expected deaths based on US mortality, and standardized mortality ratios[a] (SMR), by calendar year of certification

Cause of death		Calendar year of certification				P-trend
		< 1940	1940-49	1950-59	1960+	
	Persons	2,275	5,578	18,750	116,826	
	Person-years	92,669	214,513	595,281	1,937,002	
All causes	Observed	1,374	1,845	2,159	1,967	
	Expected	1,848.8	2,548.5	3,017.7	3,170.7	
	SMR	0.7[c]	0.7[c]	0.7[c]	0.6[c]	< 0.0001
All malignant neoplasms	Observed	318	530	741	569	
	Expected	354.6	658.0	916.0	799.9	
	SMR	0.9	0.8[c]	0.8[c]	0.7[c]	0.002
Lung	Observed	34	106	193	96	
	Expected	47.4	139.7	232.9	157.5	
	SMR	0.7	0.8[c]	0.8[c]	0.6[c]	0.23
Breast[b]	Observed	78	97	127	123	
	Expected	50.9	91.3	140.3	148.1	
	SMR	1.5[c]	1.1	0.9	0.8[c]	< 0.0001
Leukemia	Observed	16	22	22	43	
	Expected	12.7	21.9	31.2	44.5	
	SMR	1.3	1.0	0.7	1.0	0.42

[a] Number of observed deaths divided by number of expected deaths.
[b] Female technologists only.
[c] $P < 0.05$.

Table 5. Female breast cancer deaths and relative risks, by year first certified and number of years certified as a radiologic technologist

Year first certified	Number of years certified[a]				Total	P-trend
	< 10	10-19	20-29	30+		
Breast cancer deaths						
1960+	87	36	0	0	123	
1950-59	37	64	26	0	127	
1940-49	25	30	35	7	97	
< 1940	17	22	25	14	78	
Total	166	152	86	21	425	
Relative risks[b]						
1960+	1.0[c]	1.0	—	—		0.71
1950-59	1.1	1.4	1.0	—		0.30
1940-49	1.1	1.6	2.1	1.7		0.81
< 1940	1.0	1.9	2.8	3.5		< 0.001

[a] Number of years certified was computed using a 10-year lag interval.
[b] Relative risks were adjusted for attained age and calendar year of follow-up.
[c] Referent group.

were higher for both acute, myelogenous, and monocytic leukemia and CLL among those first certified before 1940 compared with those certified in 1940 or later.

Discussion

The three *a priori* cancers of interest were leukemia, breast, and lung. These sites were chosen because of their known inducibility by ionizing radiation.[19] The thyroid is also radiosensitive but mortality is not a good indicator of thyroid cancer risk and few deaths were observed. Leukemia, the hallmark of radiation-induced cancers, was not elevated significantly in this study, suggesting that the overall cumulative exposure experienced by the more than 143,000 radiologic technologists was likely to be relatively low. Other occupational groups of radiologists in the US[4,5]

Table 6. Leukemia deaths and relative risks, by year first certified and number of years certified as a radiologic technologist

Year first certified	Number of years certified				Total	*P*-trend
	< 10	10-19	20-29	30+		
Acute, myeloid, and monocytic leukemia deaths[a]						
≥ 1940	22	15	19	10	66	
< 1940	2	0	2	4	8	
Total	24	15	21	14	74	
Relative risks[b]						
≥ 1940	1.0[c]	0.8	1.5	1.8		0.38
< 1940	2.5	—	2.0	2.0		0.99
Chronic lymphocytic leukemia deaths[d]						
≥ 1940	2	1	5	3	11	
< 1940	2	0	1	4	7	
Total	4	1	6	7	18	
Relative risks[b]						
≥ 1940	1.0[c]	0.5	1.5	1.0		0.93
< 1940	5.0	—	2.5	3.0		0.99

[a] ICD-8th Revision, 204.0, 205-207.0.[14]
[b] Relative risks are adjusted for attained age, gender, and calendar year of follow-up.
[c] Referent group.
[d] ICD-8th Revision, 204.1 and 204.9.[14]

and in China[8] have experienced significant leukemia excesses but cumulative exposures, estimated at about 1 Sv, were sufficient to cause reductions in lymphocyte blood counts. Large combined series of nuclear workers also have reported a significant dose-related leukemia mortality.[10] The relative risk coefficient for leukemia is by far the highest of all radiogenic cancers.[19]

We found no significant increased risk for either acute, myelogenous, and monocytic leukemia or CLL. The patterns of risk for both groups of leukemia were very similar, which is noteworthy since CLL has never been linked to radiation in any study.[19] The 74 deaths due to acute, myelogenous, and monocytic leukemia should have been sufficient to identify a fivefold risk at 1 Sv.[19] At 20 mSv, the predicted SMR would have been about 1.8; at 10 mSv about 1.4. The lack of a significant excess of acute, myelogenous, and monocytic leukemia in our series could be due to missed or misclassified deaths during the early years, a healthy worker effect, an overall cumulative exposure that was too small to result in a detectable excess, or chance.

Lung cancer, which is increased in atomic bomb survivors[20] and in patients given radiotherapy for ankylosing spondylitis,[21] Hodgkin's disease,[22] and breast cancer,[23] has recently been found not to be increased following low-dose fractionated fluoroscopic X-ray exposures that cumulate as high as 1 Sv.[24,25] The absence in our study of a lung cancer risk with occupational exposure to fractionated doses is consistent with findings from diagnostic medical series.

The breast cancer findings are generally consistent with a radiation effect. Compared with the US population, the SMR was elevated significantly among the 13,284 women certified for the longest time, over 30 years, and among the 1,890 women who were first certified as technologists before 1940, when exposures were likely greatest. These findings were supported by an internal analysis revealing a significant trend with number of years certified for women first certified before 1940, but not after. Young women with tuberculosis who experienced fractionated low-dose X-ray fluoroscopy exposures over a period of several years have been reported to be at increased risk of breast cancer,[26] with the RR at 1 Sv being about 1.6. Our data are consistent with the possibility that radiation exposure received by young women who worked prior to and during World War II was relatively high and sufficient to increase the risk of breast cancer many years later.

Unfortunately, number of years certified was our best available exposure indicator for these mortality analyses. Since the ARRT requires a test for certification, we are aware that some percentage of technologists renew their certification annually even when not working in the field to avoid having to retest following a lapse. Thus, number of years certified is, at best, a crude measure of exposure. Also, we were not able to adjust for potential confounding from other breast cancer risk-factors. The potential for confounding is suggested by the significant deficit seen for cervical cancer (SMR = 0.27). Risk factors for cervical cancer include multiparity and low social class, *i.e.*, factors which are also associated with low breast cancer risk.

Because most decedents had not completed the 16-page mail questionnaire, we do not have reproductive data on individual women who died of breast cancer. Data from the more than 69,000 female technologists who completed the questionnaire suggested that, among women certified for 30 years or more, those who were certified before 1940 were much more likely to be nulliparous than those certified in the 1940s, 1950s, or 1960s (60 percent *cf* 40 percent, 22 percent, and 17 percent, respectively). Age at first birth followed a similar pattern, with a greater percentage of early registrants having their first birth at age 30 or greater (53 percent *cf* 29 percent, 11 percent, and eight percent). Patterns for other breast cancer risk factors, including age at menarche, age at menopause, family history of breast cancer, and personal history of breast biopsy, were less consistent.

During a manual review of records stored at the ARRT, it came to our attention that many of the early registrants were nuns. Since nuns are at increased risk of breast cancer,[27] we attempted to evaluate this as a possible confounder. A search of the computerized database for titles of 'Sister' or 'SR,' identified 1,104 nuns. The nuns comprised one percent of the women in the entire cohort but represented almost 24 percent of the 1,890 women certified before 1940. They accounted for seven percent of all breast cancer deaths and 30 percent of breast cancer deaths among the pre-1940 registrants. Analyses adjusted for attained age and calendar year of follow-up revealed no difference in the breast cancer mortality experience of nuns compared with other female technologists (SMR = 1.1, CI = 0.8-1.6).

For completeness, it is informative to compare this mortality analysis with results of our previous analyses of prevalent breast cancers reported on questionnaires.[12,13] The prevalence study was larger with 528 breast cancers compared with 425 breast cancer deaths in the current analysis, although the two populations are not totally independent. Among the 3,156 women (528 cases, 2,628 controls) included in the case-control study, there were 50 women (47 cases, three controls) who died of breast cancer and are also included in the mortality analysis. Employment as a radiologic technologist was not found to increase the risk of breast cancer in the case-control study. In contrast to the current analysis, we were able to adjust for possible confounding due to reproductive history and other factors. A notable strength of the prevalence study was that the standard breast cancer risk-factors were observed, adding some assurance that the absence of a radiation association was not a spurious finding.

Strengths of the current analysis include the large population size, with more than 143,000 workers known to be exposed to low-dose ionizing radiation over a period of many years; the extended follow-up, nearly 20 years on average, which would have been sufficient to reveal excess radiation effects; and the nearly complete follow-up with regard to mortality using local and national database resources. Limitations include the absence of complete dosimetry data, especially for the early workers and for most subjects who died; number of years certified, the only exposure indicator available for decedents, is not equivalent to number of years worked and this added additional misclassification to our surrogate measure of exposure; and reproductive histories for women who died were not available and could have confounded some of the observations.

In summary, an excess of breast cancer among women with long-term certification who were first certified before 1940 is consistent with a radiation effect. However, possible misclassification in exposure and potential confounding by reproductive history preclude a causal interpretation. The absence of increased risks for acute, myeloid, and monocytic leukemia and skin cancer are noteworthy. With the possible exception of women who began working in the 1920s and 1930s, the mortality experience of the 143,517 radiologic technologists studied does not demonstrate any remarkable patterns to suggest that their occupational exposures have significantly affected their health.

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References

1. United Nations Scientific Committee on the Effects of Atomic Radiation. *Genetic and Somatic Effects of Ionizing Radiation*. New York, NY (USA): United Nations, 1986; Pub. E.86.IX.9.
2. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. New York, NY (USA): United Nations, 1993; Pub. E.94.IX.2.

3. Jablon S, Miller RW. Army technologists: 29-year follow up for cause of death. *Radiology* 1978; **126**: 677-9.
4. March HC. Leukemia in radiologists. *Radiology* 1944; **43**: 275-8.
5. Lewis EB. Leukemia, multiple myeloma, and aplastic anemia in American radiologists. *Science* 1963; **142**: 1492-4.
6. Smith PG, Doll R. Mortality from cancer and all causes among British radiologists. *Br J Radiol* 1981; **54**: 187-94.
7. Matanoski GM, Sternberg A, Elliott EA. Does radiation exposure produce a protective effect among radiologists? *Health Phys* 1987; **52**: 637-43.
8. Wang JX, Inskip PD, Boice JD Jr, Li BX, Zhang JY, Fraumeni JF Jr. Cancer incidence among medical diagnostic x-ray workers in China, 1950 to 1985. *Int J Cancer* 1990; **45**: 889-95.
9. Gilbert ES, Cragle DL, Wiggs LD. Updated analyses of combined mortality data for workers at the Hanford Site, Oak Ridge National Laboratory, and Rocky Flats Weapons Plant. *Radiat Res* 1993; **136**: 408-21.
10. Cardis E, Gilbert ES, Carpenter L, *et al.* Effects of low doses and low dose rates of external ionizing radiation: Cancer mortality among nuclear industry workers in three countries. *Radiat Res* 1995; **142**: 117-32.
11. Boice JD Jr, Mandel JS, Doody MM, Yoder RC, McGowan R. A health survey of radiologic technologists. *Cancer* 1992; **69**: 586-98.
12. Boice JD Jr, Mandel JS, Doody MM. Breast cancer among radiologic technologists. *J Am Med Assoc* 1995; **274**: 394-401.
13. Doody MM, Mandel JS, Boice JD Jr. Employment practices and breast cancer among radiologic technologists. *J Occup Environ Med* 1995; **37**: 321-7.
14. National Center for Health Statistics. *International Classification of Diseases, Adapted for Use in the United States, Eighth Revision.* Washington, DC: US Government Printing Office, 1967; USPHS Pub. No. 1693.
15. Monson RR. Analysis of relative survival and proportional mortality. *Comput Biomed Res* 1974; **7**: 325-32.
16. Breslow NB, Day NE. *Statistical Methods in Cancer Research.* Lyon, France: International Agency for Research on Cancer, 1987; IARC Sci. Pub. No. 82.
17. Breslow NB, Lubin JH, Marek P, Langholz B. Multiplicative models and cohort analysis. *J Am Stat Assoc* 1983; **78**: 1-12.
18. Preston DL, Lubin JH, Pierce DA. *EPICURE User's Guide.* Seattle, WA (USA): Hirosoft International Corporation, 1993.
19. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation.* New York, NY (USA): United Nations, 1994; Pub. E.94.IX.11.
20. Pierce DA, Shimizu Y, Preston DL, Vaeth M, Mabuchi K. Studies of the mortality of atomic bomb survivors. Report 12, Part I. Cancer: 1950-1990. *Radiat Res* 1996; **146**: 1-27.
21. Weiss HA, Darby SC, Fearn T, *et al.* Leukemia mortality after x-ray treatment for ankylosing spondylitis. *Radiat Res* 1995; **142**: 1-11.
22. van Leeuwen FE, Somers R, Taal BG, *et al.* Increased risk of lung cancer, non-Hodgkin's lymphoma, and leukemia following Hodgkin's disease. *J Clin Oncol* 1989; **7**: 1046-58.
23. Inskip PD, Stovall M, Flannery JT. Lung cancer risk and radiation dose among women treated for breast cancer. *J Natl Cancer Inst* 1994; **86**: 983-8.
24. Davis FG, Boice JD Jr, Hrubec Z, *et al.* Cancer mortality in a radiation-exposed cohort of Massachusetts tuberculosis patients. *Cancer Res* 1989; **49**: 6130-6.
25. Howe GR. Lung cancer mortality between 1950 and 1987 after exposure to fractionated moderate-dose-rate ionizing radiation in the Canadian fluoroscopy chart study and a comparison with lung cancer mortality in the atomic bomb survivor study. *Radiat Res* 1995; **142**: 295-304.
26. Boice JD Jr, Preston D, Davis FG, Monson RR. Frequent chest X-ray fluoroscopy and breast cancer incidence among tuberculosis patients in Massachusetts. *Radiat Res* 1991; **125**: 214-22.
27. Fraumeni JF Jr, Lloyd JW, Smith EM, Wagoner JK. Cancer mortality among nuns: role of marital status in etiology of neoplastic disease in women. *J Natl Cancer Inst* 1969; **42**: 455-68.