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Radiology

ORIGINAL RESEARCH ■ MEDICAL PHYSICS

Long-term Mortality in 43 763 U.S. Radiologists Compared with 64 990 U.S. Psychiatrists[1]

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Purpose: To compare mortality rates from all causes, specific causes, total cancers, and specific cancers to assess whether differences between radiologists and psychiatrists are consistent with known risks of radiation exposure and the changes in radiation exposure to radiologists over time.

Materials and Methods: The authors used the American Medical Association Physician Masterfile to construct a cohort of 43 763 radiologists (20% women) and 64 990 psychiatrists (27% women) (comparison group) who graduated from medical school in 1916–2006. Vital status was obtained from record linkages with the Social Security Administration and commercial databases, and cause of death was obtained from the National Death Index. Poisson regression was used to estimate relative risks (RRs) and 95% confidence intervals (CIs) for all causes and specific causes of death.

Results: During the follow-up period (1979–2008), 4260 male radiologists and 7815 male psychiatrists died. The male radiologists had lower death rates (all causes) compared with the psychiatrists (RR = 0.94; 95% CI: 0.90, 0.97), similar cancer death rates overall (RR = 1.00; 95% CI: 0.93, 1.07), but increased acute myeloid leukemia and/or myelodysplastic syndrome death rates (RR = 1.62; 95% CI: 1.05, 2.50); these rates were driven by those who graduated before 1940 (RR = 4.68; 95% CI: 0.91, 24.18). In these earliest workers (before 1940) there were also increased death rates from melanoma (RR = 8.75; 95% CI: 1.89, 40.53), non-Hodgkin lymphoma (NHL) (RR = 2.69; 95% CI: 1.33, 5.45), and cerebrovascular disease (RR = 1.49; 95% CI: 1.11, 2.01). The 208 deaths in female radiologists precluded detailed investigation, and the number of female radiologists who graduated before 1940 was very small (n = 47).

Conclusion: The excess risk of acute myeloid leukemia and/or myelodysplastic syndrome mortality in radiologists who graduated before 1940 is likely due to occupational radiation exposure. The melanoma, NHL, and cerebrovascular disease mortality risks are possibly due to radiation. The authors found no evidence of excess mortality in radiologists who graduated more recently, possibly because of increased radiation protection and/or lifestyle changes.

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Internationally, it has been estimated that there are 2.3 million medical radiation workers, and they comprise about half of the workforce exposed to manmade sources of radiation (1). It is important to continue to study occupational groups who are exposed to radiation to determine if radiation protection measures are adequate (2). Patterns of mortality in radiologists can also contribute more generally to our understanding of the long-term effects of protracted low-level radiation exposure. Special features of radiologists compared with other radiation-exposed populations include generally good health compared with patient populations, the potential for long-term protracted radiation exposures, and higher doses in the past than most other radiation worker cohorts such as nuclear workers (2).

There have been eight epidemiologic studies of medical radiation worker cohorts (3,4), but only two include radiologists with long-term follow-up and both were relatively small (5–9). The British cohort of radiologists who were registered with a radiologic society between 1897 and 1979 (n = 2733) was followed up for mortality through 1997 (5–7). The U.S. cohort included 6500 male radiologists who were members of a professional society of radiologists and were followed up initially between 1920 and 1969 and subsequently, with the last mortality follow-up ending in 1974 (8,9).

We conducted a record linkage study using a nationwide listing of all U.S. physicians to identify a cohort of 43 763 radiologists and a comparison group of 64 990 psychiatrists, the latter with a low probability of occupational exposure to ionizing radiation. We performed this study to compare mortality rates attributed to all causes, specific causes, total cancers, and specific cancers to assess whether differences between radiologists and psychiatrists are consistent with known risks of radiation exposure and the changes in radiation exposure to radiologists over time.

Advances in Knowledge

- The study included 43 763 radiologists and 64 990 psychiatrists (comparison group) who graduated from medical school in 1916–2006; in the radiologists who graduated after 1940, there was no evidence of increased mortality from radiation-related causes such as cancer or cardiovascular disease.
- In the radiologists who graduated before 1940, there was an increased risk of mortality from leukemia and/or myelodysplastic syndrome (relative risk [RR] = 4.68; 95% confidence interval [CI]: 0.91, 24.18) that was likely related to their occupational radiation exposure.
- There was also increased mortality from melanoma (RR = 8.75; 95% CI: 1.89, 40.53), non-Hodgkin lymphoma (RR = 2.69; 95% CI: 1.33, 5.45), and cerebrovascular disease (RR = 1.49; 95% CI: 1.11, 2.01) in those that graduated before 1940, and this is possibly due to occupational radiation exposure.

Materials and Methods

Study Design

The study received institutional review board exemption as there was no direct contact with the study population.

The cohort was constructed by using membership listings from the American Medical Association (AMA). We obtained individual-level physician membership data from the AMA Physician Masterfile, which includes all physicians who practiced in the United States since 1902 regardless of whether they have ever been members of the AMA (*http://www.ama-assn.org/ama/pub/about-ama/physician-data-resources/physician-masterfile.page*). The AMA enrolls all U.S. physicians at the time they enter accredited medical schools or, in the case of international medical graduates, upon entry to an accredited postgraduate residency training program or when they obtain a state license in the United States. Additional professional certification information is added to the Masterfile record as they progress in their careers. The AMA updates their Masterfile database weekly with the information described earlier, self-reported physician survey data, and data from residency training programs, medical specialty boards, state licensing organizations, and other databases. The Masterfile includes basic demographic information, up to two medical specialties per physician (either self-declared or from residency programs), vital status, and date but not cause of death. The medical specialty information is updated and confirmed with use of several mechanisms. Every year, one-third of the physicians receive a self-administered annual survey that includes questions about current address, type of practice, and specialty. Thus, the entire group of physicians is contacted every 3 years. The response rate to the survey varies but is approximately 40%. If a physician does not ever complete or update a survey, the specialty for his or her most recent residency training is maintained in the file. Residency training information is obtained from the American Association of Medical Colleges by means of a data sharing agreement.

Physicians were eligible for the current cohort if they had a first or second specialty of radiology, including abdominal radiology, cardiothoracic

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Abbreviations:
AMA = American Medical Association
CI = confidence interval
NHL = non-Hodgkin lymphoma
RR = relative risk

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Conflicts of interest are listed at the end of this article.

radiology, diagnostic radiology, musculoskeletal radiology, nuclear radiology, and pediatric radiology. Interventional radiologists, defined as those who had this as their specialty or subspecialty in the AMA Masterfile, were excluded from the current analysis as we are studying them separately in a cohort of physicians who perform fluoroscopically guided procedures. We selected a sample of physicians with a primary or secondary specialty of psychiatry as the comparison group because of a very low probability of occupational exposure to radiation. The stratified random sample was selected to ensure at least a 1:1 ratio (psychiatrists:radiologists) in each of the strata defined according to birth year (5-year categories) and sex.

Outcome Ascertainment

We conducted a series of record linkages to ascertain identifying information that was not available in the AMA database and then matched the cohort with the Social Security Administration database to determine vital status. The physicians who were confirmed or presumed to be deceased were matched with the National Death Index (*http://www.cdc.gov/nchs/ndi.htm*). To obtain identifying information, we used commercial databases such as the Pension Benefits Incorporated, TransUnion, Accurint, and Fastdata databases and also used interactive tracing to obtain additional identifying information for individuals who could not be traced successfully by using the other sources. Uncertain matches were reviewed manually. Vital status was then confirmed with the Social Security Administration. We submitted records for physicians who were confirmed or presumed to be deceased for whom we had a date of death and for those deceased physicians for whom we did not have a date of death to the National Death Index. Because the National Death Index includes deaths for 98% of the U.S. population (10), subjects for whom no record of death was found were assumed to be alive.

Statistical Analysis

Physicians were followed up from January 1, 1979 (date of the start of the National Death Index), or from 1 year after medical school graduation (if after 1979) until date of death, loss to follow-up, or December 31, 2008. Follow-up was limited to deaths that occurred before age 85 years because cause of death is reported less reliably after that age (7). Poisson regression analysis was used to estimate relative risks (RRs) and 95% confidence intervals (CIs) for all causes of death and specific causes for radiologists versus psychiatrists. All analyses were adjusted (by means of stratification) for sex, year of birth, and attained age—the latter two characteristics in 5-year groups. We also compared the observed number of deaths from various causes to the expected number by means of standardized mortality ratios on the basis of rates in the general U.S. population, adjusted for age, sex, and calendar year of death.

We used the year of medical school graduation plus 1 year as a proxy for the year first exposed to radiation. Because occupational radiation exposures to noninterventional radiologists have been reduced over time owing to improved protection (11–14), the year of medical school graduation is a proxy for exposure level. We conducted a sensitivity analysis that was restricted to those physicians who were dead or confirmed to be alive through the Social Security Administration to assess whether there was bias related to completeness of follow-up. All analyses were conducted with software (Epicure; Risk Sciences International, Ottawa, Ontario, Canada).

Results

We identified a cohort of 43 763 radiologists (8851 women [20%]) and 64 990 psychiatrists (17 493 women [27%]) from the AMA Masterfile. The cohort consists of physicians who started practicing as early as 1916 and who were still alive in 1979, which is when the National Death Index was introduced.

Overall, radiologists were slightly younger and slightly more likely to have graduated from medical school in 1960 or later compared with psychiatrists. Radiologists were also more likely than psychiatrists to be born in the United States (Table 1).

In the male cohort, 4260 of 43 763 radiologists (12%) and 7815 of 47 443 psychiatrists (16%) were confirmed to have died between 1979 and 2008 (Table 2). Cause of death was not ascertained for 133 (3%) of the 4260 male radiologists and 337 (4%) of the 7815 male psychiatrists. In the female cohort, 208 (2%) of the 8851 radiologists and 524 (3%) of the 17 493 psychiatrists died during the follow-up period. Overall, the radiologists and the psychiatrists had substantially lower death rates than the general population (standardized mortality ratio = 0.47 for radiologists and 0.52 for psychiatrists) (Table E1 [online]). Given the small number of female radiologists, our analyses focused on men; Table E1 (online) provides additional details about the female subjects.

The male radiologists had a lower risk of death overall than did the male psychiatrists (RR = 0.94; 95% CI: 0.90, 0.97) but a similar risk of death from any cancer (RR = 1.00; 95% CI: 0.93, 1.07). There was an increased risk of skin cancer mortality in the radiologists who graduated before 1940 (RR = 6.38; 95% CI: 1.75, 23.20) that was driven by an excess of melanoma (RR = 8.75; 95% CI: 1.89, 40.53) (Table 2).

Overall, there was an increased risk of death for all myeloid leukemias (RR = 1.43; 95% CI: 1.00, 2.05), which was largely due to acute myeloid leukemia and/or myelodysplastic syndrome in those who graduated before 1940 (RR = 4.68; 95% CI: 0.91, 24.18) (Table 3). There was also an increased risk of death from all lymphoid malignancies (lymphomas) in these earliest radiologists (RR = 2.24; 95% CI: 1.31, 3.86) because of an increased risk of death from NHL (RR = 2.69; 95% CI: 1.33, 5.45). There were no significantly increased risks of cancer mortality in those who graduated after 1940 for all solid cancers, hematologic malignancies, or site-specific solid cancers.

In the deaths from noncancer causes, we noted an excess risk of cerebrovascular deaths in the radiologists who graduated before 1940 (RR = 1.49; 95% CI: 1.11, 2.01) (Table 4). However,

Table 1

Description of the Study Cohort

Parameter	Men: Radiologists (n = 34 912)	Men: Psychiatrists (n = 47 497)	Women: Radiologists (n = 8851)	Women: Psychiatrists (n = 17 493)	Total: Radiologists (n = 43 763)	Total: Psychiatrists (n = 64 990)
Year of birth						
1894–1903	324 (1)	692 (1)	16 (0.2)	45 (0.3)	340 (1)	737 (1)
1904–1913	1131 (3)	2293 (5)	40 (0.5)	74 (0.4)	1171 (3)	2367 (4)
1914–1923	2471 (7)	4462 (9)	104 (1)	232 (1)	2575 (6)	4694 (7)
1924–1933	3952 (11)	6904 (15)	231 (3)	481 (3)	4183 (9)	7385 (11)
1934–1943	6051 (17)	8225 (17)	576 (7)	1163 (7)	6627 (15)	9388 (14)
1944–1953	6460 (19)	9881 (21)	1589 (18)	3358 (19)	8049 (18)	13239 (20)
1954–1963	6242 (18)	8268 (17)	2540 (29)	5378 (31)	8782 (21)	13646 (21)
1964–1973	5397 (16)	5045 (11)	2455 (28)	4550 (26)	7852 (18)	9595 (15)
1974–1983	2884 (8)	1727 (4)	1300 (15)	2212 (13)	4184 (9)	3939 (7)
Graduation year						
<1940	1426 (4)	2842 (6)	47 (1)	111 (1)	1473 (3)	2953 (4)
1940–1959	6201 (18)	10753 (23)	335 (3)	669 (4)	6536 (15)	11422 (18)
1960–1979	12002 (34)	17098 (36)	1847 (21)	3615 (20)	13849 (32)	20713 (32)
1980+	15283 (44)	16804 (35)	6622 (75)	13098 (75)	21905 (50)	29902 (46)
Country of birth						
United States	27306 (78)	33014 (70)	6183 (70)	10824 (62)	33489 (77)	43838 (67)
Other	4826 (14)	8735 (18)	1495 (17)	2918 (17)	6321 (14)	11653 (18)
Unknown	2780 (8)	5748 (12)	1173 (13)	3751 (21)	3953 (9)	9499 (15)
Median age at entry to cohort (y)	32	35	28	28	30	32
Median age at exit from cohort (y)	58	62	47	48	55	58
Median follow-up (y)	25	26	19	19	23	24
No. of deaths						
Graduation year						
<1940	712 (17)	1415 (18)	19 (9)	44 (9)	731 (17)	1459 (18)
1940–1959	2427 (57)	4389 (56)	85 (41)	179 (34)	2512 (56)	4568 (55)
1960–1979	973 (23)	1689 (22)	70 (34)	175 (33)	1043 (23)	1864 (22)
1980+	148 (3)	322 (4)	34 (16)	126 (24)	182 (4)	448 (5)
Time since graduation (y)						
<10	68 (2)	152 (2)	9 (4)	49 (9)	77 (2)	201 (2)
10–19	179 (4)	379 (5)	21 (10)	81 (16)	200 (4)	460 (5)
20–29	406 (10)	713 (9)	41 (20)	96 (18)	447 (10)	809 (10)
30–39	819 (19)	1317 (17)	55 (26)	83 (16)	874 (20)	1400 (17)
40+	2788 (65)	5254 (67)	82 (40)	215 (41)	2870 (64)	5469 (66)
Total deaths	4260 (100)*	7815 (100)†	208 (100)‡	524 (100)§	4468 (100)	8339 (100)

Note.—Except where indicated, data are numbers of patients, with percentages in parentheses.

* Cause of death was missing in 133 cases.

† Cause of death was missing in 337 cases.

‡ Cause of death was missing in 14 cases.

§ Cause of death was missing in 55 cases.

there were decreased risks of infectious diseases (RR = 0.43; 95% CI: 0.34, 0.55)—primarily human immunodeficiency virus (RR = 0.32; 95% CI: 0.22, 0.45) (Table 4), respiratory diseases (RR = 0.85; 95% CI: 0.73, 0.99), accidents (RR = 0.77; 95% CI: 0.67, 0.89), and suicides (RR = 0.66; 95% CI: 0.55, 0.80). Many of these decreases were greatest in the physicians who graduated most recently (1980 and later).

In a sensitivity analysis, we restricted the subjects to those who were confirmed as dead or alive by the Social Security Administration, and the results were essentially equivalent to those with the full analyses (Table E2 [online]).

There were no clear increases in mortality in the female radiologists compared with female psychiatrists (Table 5). Overall, total mortality was lower in female radiologists compared with female psychiatrists, but total cancer risks

Table 2

RRs and 95% CIs of Death from All Causes, All Cancers, and Site-specific Cancers in Male Radiologists (n = 34 912) and Male Psychiatrists (n = 47 497) according to Year of Medical School Graduation

Cause of Death	<1940 Deaths*	<1940 RR†	1940–1959 Deaths*	1940–1959 RR†	1960–1979 Deaths*	1960–1979 RR†	1980+ Deaths*	1980+ RR†	*P* Value for Trend	Total Deaths*	Total RR†
All causes of death	712/1415	0.96 (0.88, 1.05)	2427/4389	0.98 (0.93, 1.03)	973/1689	0.87 (0.81, 0.95)	148/322	0.66 (0.54, 0.81)‡	<.001	4260/7815	0.94 (0.90, 0.97)‡
All malignant neoplasms	190/321	1.12 (0.94, 1.34)	745/1330	0.99 (0.90, 1.08)	337/528	0.96 (0.84, 1.10)	34/57	0.96 (0.62, 1.48)	>.50	1306/2236	1.00 (0.93, 1.07)
Site-specific neoplasms											
Lip, oral cavity, pharynx	3/6	0.95 (0.24, 3.81)	13/25	0.91 (0.47, 1.78)	11/7	2.50 (0.95, 6.54)	1/1	2.35 (0.15, 37.7)	.35	28/39	1.24 (0.76, 2.02)
Digestive organs	58/100	1.12 (0.80, 1.53)	203/389	0.92 (0.78, 1.09)	104/152	1.02 (0.80, 1.32)	8/13	0.97 (0.40, 2.36)	>.50	373/654	0.97 (0.86, 1.12)
Esophagus	6/3	3.67 (0.92, 14.7)	21/0.38	1.00 (0.58, 1.69)	9/12	1.11 (0.46, 2.64)	0/1	NA	.22	36/54	1.14 (0.75, 1.74)
Stomach	5/10	0.97 (0.33, 2.83)	18/30	1.05 (0.59, 1.89)	14/22	0.98 (0.50, 1.92)	2/0	NA	.38	39/62	1.06 (0.71, 1.59)
Colon	30/48	1.20 (0.76, 1.89)	75/130	1.01 (0.76, 1.35)	29/41	1.07 (0.66, 1.73)	4/6	1.00 (0.28, 3.55)	>.50	138/225	1.06 (0.86, 1.31)
Rectum and rectosigmoid junction	2/5	0.75 (0.14, 3.88)	11/17	1.14 (0.53, 2.44)	5/10	0.70 (0.24, 2.05)	0/1	NA	>.50	18/33	0.91 (0.51, 1.62)
Liver and intrahepatic bile duct	3/6	0.95 (0.24, 3.82)	21/35	1.04 (0.61, 1.79)	13/16	1.20 (0.58, 2.51)	0/2	NA	>.50	37/59	1.05 (0.70, 1.59)
Pancreas	12/25	0.92 (0.46, 1.83)	53/123	0.76 (0.55, 1.05)	28/45	0.94 (0.58, 1.51)	2/3	1.12 (0.18, 6.85)	>.50	95/196	0.83 (0.65, 1.06)
Respiratory and intrathoracic organs	27/56	0.91 (0.57, 1.44)	167/280	1.05 (0.86, 1.27)	60/88	1.04 (0.75, 1.44)	3/8	0.70 (0.18, 2.71)	>.50	257/432	1.02 (0.88, 1.19)
Lung and bronchus	25/56	0.84 (0.53, 1.35)	162/273	1.04 (0.86, 1.27)	58/84	1.06 (0.75, 1.48)	3/8	0.70 (0.18, 2.71)	>.50	248/421	1.01 (0.87, 1.19)
Bone	0/0	NA	0/3	NA	3/2	2.27 (0.37, 13.7)	0/0	NA	.06	3/5	0.95 (0.22, 3.98)
All skin	10/3	6.38 (1.75, 23.20)‡	26/35	1.29 (0.78, 2.14)	16/34	0.67 (0.37, 1.23)	1/5	0.31 (0.04, 2.75)	.004‡	53/77	1.12 (0.79, 1.59)
Melanoma	9/2	8.75 (1.89, 40.53)‡	23/25	1.59 (0.90, 2.80)	14/27	0.75 (0.39, 1.43)	1/4	0.41 (0.04, 3.80)	.005‡	47/58	1.32 (0.90, 1.95)
Other nonepithelial skin	1/1	1.75 (0.11, 28.01)	3/10	0.53 (0.15, 1.94)	2/7	0.40 (0.08, 1.92)	0/1	NA	>.50	6/19	0.50 (0.20, 1.27)
Soft tissue	0/1	NA	11/23	0.83 (0.41, 1.71)	9/10	1.27 (0.51, 3.13)	2/0	NA	.2	22/34	1.04 (0.61, 1.78)
Breast	0/0	NA	1/2	0.86 (0.08, 9.45)	0/2	NA	0/0	NA	.24	1/4	0.39 (0.04, 3.53)
Genitourinary organs	45/96	0.89 (0.63, 1.27)	146/253	1.03 (0.84, 1.26)	40/71	0.93 (0.63, 1.38)	5/3	3.23 (0.75, 13.8)	.36	236/423	1.0 (0.85, 1.17)
Prostate	30/76	0.75 (0.49, 1.15)	92/185	0.89 (0.69, 1.14)	26/42	1.05 (0.64, 1.73)	0/1	NA	>.50	148/304	0.88 (0.72, 1.07)
Urinary bladder	9/14	1.23 (0.53, 2.84)	26/30	1.55 (0.92, 2.62)	5/5	1.50 (0.43, 5.22)	1/0	NA	>.50	41/49	1.50 (0.99, 2.27)
Kidney and renal pelvis	6/6	1.84 (0.59–5.70)	26/36	1.27 (0.77, 2.11)	8/23	0.55 (0.25, 1.25)	3/1	5.60 (0.57, 55.24)	.095	43/66	1.13 (0.77–1.66)
Brain and central nervous system (including benign)	1/11	0.17 (0.02, 1.31)	26/59	0.77 (0.49, 1.23)	24/37	0.92 (0.55, 1.54)	6/12	0.70 (0.26, 1.88)	.3	57/119	0.76 (0.56, 1.05)
Brain and central nervous system (malignant)	1/9	0.20 (0.02, 1.61)	23/54	0.75 (0.46, 1.22)	22/34	0.92 (0.53, 1.56)	6/11	0.74 (0.27, 2.03)	.45	52/108	0.76 (0.55, 1.06)
Total leukemia	11/11	1.91 (0.83, 4.41)	44/59	1.31 (0.89, 1.94)	20/33	0.91 (0.52, 1.58)	2/2	1.25 (0.17, 9.49)	>.50	77/105	1.23 (0.92, 1.66)
Leukemia excluding chronic lymphocytic leukemia	5/3	3.27 (0.78, 13.71)	23/32	1.27 (0.74, 2.17)	14/16	1.27 (0.62, 2.61)	2/1	2.03 (0.18, 23.11)	>.50	44/52	1.39 (0.93, 2.09)
Total lymphoma	20/13	2.83 (1.41, 5.70)‡	47/80	1.03 (0.72, 1.47)	27/45	0.89 (0.55, 1.43)	4/7	0.95 (0.27, 3.29)	.04	98/145	1.13 (0.87, 1.46)

* Data are numbers of radiologists/numbers of psychiatrists.

† Stratified on year of attained age, year of birth, and year of medical school graduation. Numbers in parentheses are 95% CIs. NA = not applicable.

‡ P <.05 for difference in risk between radiologists and psychiatrists is based on the Wald test.

Table 3

RRs and 95% CIs of Death from Hematopoietic and Lymphoproliferative Disorders in Male Radiologists (n = 34 912) and Male Psychiatrists (n = 46 846) according to Year of Medical School Graduation

Cause of Death	<1940		1940–1959		1960–1979		1980+		*P* Value	Total	
	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	for Trend	Deaths*	RR†
All myeloid	6/6	1.86 (0.60, 5.77)	31/42	1.30 (0.82, 2.07)	16/17	1.38 (0.70, 2.75)	3/0	NA	.30	56/65	1.43 (1.00, 2.05)‡
Acute myeloid leukemia and myelodysplastic syndrome§	5/2	4.68 (0.91, 24.18)	22/30	1.30 (0.75, 2.25)	11/10	1.61 (0.68, 3.80)	3/0	NA	.14	41/42	1.62 (1.05, 2.50)‡
Acute myeloid and monocytic leukemia	3/2	2.91 (0.48, 17.42)	16/21	1.35 (0.70, 2.59)	10/10	1.46 (0.61, 3.53)	2/0	NA	.47	31/33	1.54 (0.94, 2.53)
Myelodysplastic syndrome	2/0	NA	6/9	1.18 (0.42, 3.33)	1/0	NA	1/0	NA	.13	10/9	1.91 (0.78, 4.72)
Myeloproliferative disorders	1/3	0.63 (0.06, 6.08)	7/10	1.21 (0.46, 3.19)	5/4	1.79 (0.48, 6.71)	0/0	NA	>.50	13/17	1.27 (0.61, 2.61)
Chronic myeloid leukemia	1/1	1.90 (0.12, 30.35)	5/8	1.08 (0.35, 3.31)	4/4	1.45 (0.36, 5.82)	0/0	NA	>.50	10/13	1.26 (0.55, 2.88)
Other myeloid leukemia	0/1	NA	2/2	1.71 (0.24, 12.16)	0/3	NA	0/0	NA	.17	2/6	0.56 (0.11, 2.78)
All lymphoid and hematopoetic	34/27	2.34 (1.41, 3.87)‡	110/171	1.13 (0.89, 1.44)	52/86	0.89 (0.63, 1.26)	7/11	1.01 (0.39, 2.66)	.02‡	203/295	1.15 (0.96, 1.38)
All lymphoid	29/24	2.24 (1.31, 3.86)‡	82/136	1.06 (0.8, 1.40)	38/72	0.78 (0.52, 1.15)	4/11	0.63 (0.20, 2.01)	.01‡	153/243	1.06 (0.86, 1.30)
Non-Hodgkin lymphoma (NHL)	19/13	2.69 (1.33, 5.45)‡	46/80	1.01 (0.70, 1.55)	26/41	0.94 (0.58, 1.55)	2/6	0.57 (0.11, 2.86)	.05‡	93/140	1.12 (0.86, 1.30)
Chronic lymphocytic leukemia	2/4	0.93 (0.17, 5.08)	10/13	1.34 (0.59, 3.07)	2/6	0.51 (0.10, 2.53)	0/1	NA	>.50	14/24	1.01 (0.52, 1.96)
Acute lymphocytic leukemia	1/0	NA	2/3	1.21 (0.20, 7.28)	0/2	NA	0/1	NA	.13	3/6	0.84 (0.21, 3.40)
Other lymphoid leukemia	0/0	NA	0/2	NA	0/1	NA	0/0	NA	>.50	0/3	NA
Multiple myeloma	6/7	1.60 (0.54, 4.78)	23/35	1.16 (0.68, 1.96)	9/18	0.73 (0.33, 1.62)	0/2	NA	.39	38/62	1.04 (0.70, 1.56)
Hodgkin lymphoma	1/0	NA	1/3	0.58 (0.06, 5.58)	1/4	0.33 (0.04, 2.98)	2/1	3.06 (0.27, 34.2)	.22	5/8	0.95 (0.31, 2.92)
Other leukemias (unspecified)	4/3	2.58 (0.58, 11.54)	9/10	1.60 (0.65, 3.94)	4/7	0.89 (0.26, 3.07)	0/0	NA	>.50	17/20	1.48 (0.77, 2.83)

* Data are numbers of radiologists/numbers of psychiatrists.

† Stratified on year of attained age, year of birth, and year of medical school graduation. Numbers in parentheses are 95% CIs. NA = not applicable.

‡ $P < .05$ for difference in risk between radiologists and psychiatrists is based on the Wald test.

§ Includes all malignant, benign, and uncertain behavior.

were similar. Risk of all circulatory diseases and particularly cerebrovascular disease was notably reduced in radiologists compared with psychiatrists, albeit these are based on small numbers. The relatively small number of deaths in this group (n = 208), however, prevented detailed investigation.

Discussion

We established the largest cohort to date of radiologists who had practiced in the United States throughout the last century and a comparison group of psychiatrists unlikely to have had occupational radiation exposure. Overall, compared with the psychiatrists, the radiologists had a significantly lower risk of death from all causes and a similar risk of death from all cancers combined and most other specific causes of death, but we did observe an increased risk of acute myeloid leukemia and/or myelodysplastic syndrome, melanoma, and NHL in the radiologists who graduated before 1940—when radiation exposures would have been the highest. There was also an excess risk of cerebrovascular death in these earliest radiologists. There were no increased risks of cancer mortality or other causes of death in the radiologists who graduated after 1940.

The previous U.S. cohort of mortality to 1974 in radiologists who joined the Radiological Society of North America (RSNA) between 1920 and 1969 (9) also showed excess mortality rates for radiation-related cancers, which were only observed in the earliest radiologists (who joined the RSNA before 1940); however, follow-up was limited for those who joined after 1940. In a much larger population with longer-term follow-up, we have confirmed that excess mortality rates in U.S. radiologists are mostly restricted to those who worked before 1940. In a U.K. cohort, results of long-term follow-up suggested that excess mortality rates were restricted to those who worked before 1954 (7).

Early case studies of radiologists provided the first evidence that leukemia was a radiation-related cancer (15). Further systematic studies of U.K. and U.S. radiologists confirmed this finding

Table 4

RRs and 95% CIs of Death from Noncancer Causes in Male Radiologists (n = 34 912) and Male Psychiatrists (n = 46 846) according to Year of Medical School Graduation

	<1940		1940–1959		1960–1979		1980+		*P* Value	Total	
Cause of Death	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	for Trend	Deaths*	RR†
Infectious diseases	5/8	1.19 (0.39, 3.66)	27/87	0.54 (0.35, 0.83)‡	39/128	0.42 (0.30, 0.61)‡	13/64	0.27 (0.15, 0.49)‡	.09	84/287	0.43 (0.34, 0.55)‡
Human immunodeficiency virus	0/0	NA	3/15	0.34 (0.1, 1.18)	26/96	0.37 (0.24, 0.58)‡	10/58	0.23 (0.12, 0.44)‡	.45	39/169	0.32 (0.22, 0.45)‡
Septicemia	1/3	0.63 (0.66, 6.08)	9/36	0.43 (0.21, 0.90)‡	2/6	0.51 (0.1, 2.56)	1/1	1.06 (0.06, 17.01)	>.50	13/46	0.47 (0.26, 0.88)‡
Diseases of blood forming tissue	1/5	0.38 (0.04, 3.22)	13/19	1.22 (0.6, 2.47)	4/8	0.86 (0.25, 2.92)	1/1	1.29 (0.08, 20.6)	>.50	19/33	1.01 (0.57, 1.78)
Aplastic anemia	0/1	NA	4/2	3.67 (0.67, 20.07)	0/1	NA	0/0	NA	.20	4/4	1.89 (0.47, 7.56)
All endocrine disorders	11/27	0.77 (0.38, 1.56)	66/127	0.92 (0.68, 1.24)	33/51	1.00 (0.64, 1.56)	6/7	1.34 (0.44, 4.03)	>.50	116/212	0.94 (0.75, 1.18)
Diabetes mellitus	10/23	0.82 (0.39, 1.73)	53/89	1.05 (0.75, 1.47)	24/34	1.11 (0.66, 1.89)	1/2	0.98 (0.09, 11.25)	>.50	88/148	1.03 (0.80, 1.34)
All mental and behavioral disorders	11/16	1.30 (0.60, 2.80)	34/63	0.97 (0.64, 1.48)	10/11	1.65 (0.70, 3.95)	3/5	0.85 (0.20, 3.60)	>.50	58/95	1.30 (0.60, 2.80)
Neurologic and mental conditions	25/52	0.91 (0.56, 1.46)	120/190	1.12 (0.89, 1.41)	32/52	0.98 (0.63, 1.54)	1/6	0.23 (0.03, 1.96)	.34	178/300	1.04 (0.86, 1.25)
Alzheimer disease	5/22	0.43 (0.16, 1.14)	40/65	1.09 (0.73, 1.62)	5/9	1.08 (0.35, 3.27)	0/0	NA	.18	50/96	0.94 (0.67, 1.33)
Other degenerative diseases of the nervous system	19/18	2.02 (1.05, 3.82)	24/41	1.06 (0.64, 1.75)	6/6	1.59 (0.50, 5.06)	1/0	NA	.29	50/65	1.39 (0.96, 2.01)
All circulatory diseases	364/756	0.92 (0.81, 1.05)	944/1719	0.98 (0.90, 1.06)	290/452	1.02 (0.88, 1.18)	22/52	0.65 (0.40, 1.07)	.30	1620/2979	0.97 (0.91, 1.03)
Hypertension without heart disease	2/0	NA	3/14	0.38 (0.11, 1.32)	2/7	0.48 (0.1, 2.37)	0/0	NA	.05	7/21	0.58 (0.25, 1.37)
Ischemic heart disease	211/456	0.88 (0.75, 1.04)	563/1044	0.96 (0.87, 1.06)	176/271	1.03 (0.85, 1.24)	12/27	0.70 (0.35, 1.39)	>.50	962/1798	0.95 (0.88, 1.02)
Other diseases of heart	41/124	0.64 (0.45, 0.91)‡	149/288	0.92 (0.76, 1.12)	47/66	1.08 (0.74, 1.57)	6/14	0.64 (0.24, 1.7)	.16	243/492	0.87 (0.74, 1.01)
Cerebrovascular diseases	77/101	1.49 (1.11, 2.01)‡	133/219	1.08 (0.87, 1.34)	27/60	0.75 (0.48, 1.19)	2/6	0.45 (0.09, 2.26)	.046‡	239/386	1.12 (0.95, 1.32)
Atherosclerosis	3/9	0.66 (0.18, 2.46)	8/19	0.78 (0.34, 1.79)	2/2	3.53 (0.44, 28.5)	0/1	NA	.41	13/31	0.82 (0.43, 1.57)
Aortic aneurysm and dissection	11/27	0.78 (0.38, 1.57)	26/51	0.91 (0.56, 1.45)	6/9	1.02 (0.36, 2.90)	1/0	NA	.44	44/87	0.90 (0.63, 1.30)
All diseases of the respiratory system	36/103	0.67 (0.46, 0.98)‡	159/303	0.93 (0.77, 1.13)	28/60	0.78 (0.49, 1.23)	2/7	0.46 (0.09, 2.26)	.35	225/473	0.85 (0.73, 0.99)‡
Pneumonia and influenza	18/49	0.71 (0.41, 1.22)	38/91	0.75 (0.51, 1.1)	11/24	0.73 (0.36, 1.51)	0/3	NA	.48	67/167	0.72 (0.54, 0.96)‡
Chronic obstructive pulmonary disease and allied conditions	11/43	0.48 (0.25, 0.94)‡	77/129	1.06 (0.8, 1.41)	10/17	1.01 (0.46, 2.24)	1/3	0.59 (0.06, 5.81)	.15	99/192	0.92 (0.72, 1.18)
All gastrointestinal diseases	22/32	1.29 (0.75, 2.22)	79/118	1.19 (0.89, 1.58)	25/55	0.70 (0.43, 1.12)	7/8	1.33 (0.48, 3.70)	.22	133/213	1.07 (0.86, 1.33)
Chronic liver disease and cirrhosis	7/5	2.61 (0.83, 8.25)	36/45	1.40 (0.90, 2.17)	12/27	0.65 (0.33, 1.29)	6/1	9.35 (1.12, 78.33)	.014	61/78	1.30 (0.93, 1.82)
All genitourinary diseases	12/30	0.78 (0.40, 1.53)	42/73	1.03 (0.71, 1.51)	8/12	1.02 (0.41, 2.51)	2/0	NA	.19	64/115	1.00 (0.74, 1.36)
Nephritis, nephrotic syndrome/glomerular	6/21	0.55 (0.22, 1.36)	12/18	1.24 (0.60, 2.58)	2/6	0.47 (0.1, 2.36)	0/0	NA	.29	20/45	0.81 (0.48, 1.37)

Table 4 *(continues)*

Table 4 (continued)

RRs and 95% CIs of Death from Noncancer Causes in Male Radiologists (n = 34 912) and Male Psychiatrists (n = 46 846) according to Year of Medical School Graduation

	<1940		1940–1959		1960–1979		1980+		P Value	Total	
Cause of Death	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	for Trend	Deaths*	RR†
Accidents and adverse effects	22/46	0.90 (0.54, 1.50)	126/238	0.92 (0.74, 1.14)	118/246	0.68 (0.55, 0.85)‡	28/69	0.55 (0.36, 0.86)	.09	294/599	0.77 (0.67, 0.89)‡
Suicide and self-inflicted injury	10/21	0.90 (0.42, 1.91)	57/118	0.83 (0.61–1.15)	63/161	0.54 (0.40, 0.73)‡	26/58	0.62 (0.39, 1.00)	.21	156/358	0.66 (0.55–0.80)‡
Homicide and legal intervention	0/1	NA	4/10	0.67 (0.21–2.14)	6/16	0.56 (0.22, 1.43)	2/6	0.46 (0.09, 2.32)	>.50	12/33	0.56 (0.29–1.08)

* Data are numbers of radiologists/numbers of psychiatrists.

† Stratified on year of attained age, year of birth, and year of medical school graduation. Numbers in parentheses are 95% CIs. NA = not applicable.

‡ $P < .05$ for difference in risk between radiologists and psychiatrists is based on the Wald test.

Table 5

RRs and 95% CIs for Deaths from All Causes, All Cancers, Leukemia, and Selected Circulatory Diseases in Female Radiologists (n = 8851) and Female Psychiatrists (n = 17 493) according to Year of Medical School Graduation

	<1940		1940–1959		1960–1979		1980+		P Value	Total	
Cause of Death	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	Deaths*	RR†	for Trend	Deaths*	RR†
All causes of death	19/44	0.99 (0.57, 1.70)	85/179	1.00 (0.77, 1.30)	70/175	0.79 (0.60, 1.05)	34/126	0.58 (0.40, 0.85)	.11	208/524	0.83 (0.70, 0.97)‡
All malignant neoplasms	4/12	0.76 (0.24, 2.39)	40/71	1.15 (0.78, 1.70)	30/87	0.68 (0.45, 1.03)	18/51	0.79 (0.46, 1.36)	.32	92/221	0.86 (0.67, 1.10)
Total leukemia	0/0	NA	3/5	1.13 (0.27, 4.76)	2/4	0.96 (0.17, 5.24)	2/3	1.44 (0.24, 8.65)	>.50	7/12	1.15 (0.45, 2.92)
Leukemia excluding chronic lymphocytic leukemia	0/0	NA	0/4	NA	1/2	0.96 (0.09, 10.6)	2/2	2.2 (0.31, 15.6)	.14	3/8	0.74 (0.19, 2.78)
Acute myeloid leukemia and myelodysplastic syndrome§	0/1	NA	0/3	NA	2/0	NA	1/2	1.03 (0.09, 11.3)	.05	3/6	0.96 (0.24, 3.82)
All circulatory diseases	4/18	0.53 (0.18, 1.58)	20/54	0.85 (0.51, 1.42)	6/31	0.40 (0.17, 0.96)‡	3/11	0.68 (0.19, 2.47)	.49	33/114	0.65 (0.44, 0.97)‡
Ischemic heart disease	1/10	0.25 (0.03, 1.97)	13/22	1.33 (0.67, 2.65)	2/13	0.34 (0.07, 1.50)	3/5	1.66 (0.39, 7.07)	.11	19/50	0.89 (0.52, 1.51)
Cerebrovascular diseases	0/1	NA	2/15	0.32 (0.07, 1.43)	1/8	0.25 (0.03, 2.02)	0/1	NA	>.50	3/25	0.28 (0.08, 0.92)‡

* Data are numbers of radiologists/numbers of psychiatrists.

† Stratified on year of attained age, year of birth, and year of medical school graduation. Numbers in parentheses are 95% CIs. NA = not applicable.

‡ $P < .05$ for difference in risk between radiologists and psychiatrists is based on the Wald test.

§ Includes all malignant, benign, and uncertain behavior.

(6,16), and our results for acute myeloid leukemia are consistent with the results of those studies. The elevated risk of acute myeloid leukemia has also been shown to persist in atomic bomb survivors for more than 55 years after exposure (17).

Skin cancer mortality, particularly melanoma, was also increased in the radiologists who graduated before 1940, which is interesting because ionizing radiation is not thought to be a cause of melanoma (18). There were significant excess risks of deaths from nonmelanoma skin cancer in the United Kingdom (7) and in the previous cohort of U.S. radiologists (16), but not melanoma. Melanoma is a relatively rare cancer and, therefore, has been difficult to study in most previous radiation epidemiology cohorts. In the last cancer incidence analysis of Japanese atomic bomb survivors, there were only 17 cases, which precluded informative analysis (19). There was a nonstatistically significant dose response in U.K. nuclear workers ($n = 261$) (20) and a significant excess in the U.S. Radiologic Technologists study among those who first worked before 1950 (21). Confounding by solar ultraviolet radiation, which is a strong risk factor for melanoma (22), cannot be ruled out, but the radiologists who graduated before 1940 would have needed higher exposure to ultraviolet radiation for this to explain the patterns of results.

NHL is also not classified as a radiation-inducible cancer because of the inconsistency in findings across studies (18). There is a weak suggestion of a radiation dose response for NHL among male atomic bomb survivors, but not for female survivors (17), and an excess was observed in the U.K. radiologists—although the numbers were small ($n = 9$) (7). Again, as with melanoma, the elevated risk in the earliest radiologists is compatible with higher radiation doses but could be due to unknown confounding factors if they were more common in radiologists who graduated before 1940. Because death rates from the human immunodeficiency virus were significantly lower in the radiologists than the psychiatrists and NHL is an acquired immune deficiency syndrome–related cancer (23), this may have biased the risk estimates in those radiologists who graduated after 1940 toward the null.

An increased risk of cerebrovascular disease mortality was not reported in any of the previous radiologist cohorts (7,16) but has been observed at higher dose levels (>0.5 Gy) in atomic bomb survivors (24), after radiation therapy for breast cancer (25), and in the Mayak worker cohort (26). It is less certain whether doses less than 0.5 Gy are associated with heart disease and cerebrovascular disease, although a recent meta-analysis provided some evidence that it may be (27).

The major strengths of our study are the large size of the population, our ability to capture the majority of radiologists who practiced in the United States and were still alive in 1979, and the internal comparison group of physicians who were unlikely to have been exposed to radiation through their occupation. Our long-term follow-up of radiologists who graduated before 1940 provides an assessment of risks several decades after first exposure. We also had systematic follow-up through a large number of tracing sources, with a sensitivity analysis that excluded large follow-up biases.

The large-scale nature of the study also brought limitations, including a lack of data on whether a physician is currently practicing medicine, a lack of data about lifestyle factors, and a lack of individual occupational radiation doses. The AMA physicians' database has been used for previous surveys of the radiology workforce because it is more complete than the American College of Radiology membership (28), which is estimated to include about 75% of practicing radiologists. The American College of Radiology currently reports that about 21 000 members are diagnostic radiologists (29). In 2002, Bhargavan et al (30) estimated, by using American College of Radiology data, that there were about 25 000 radiologists practicing in the United States in 2001. Our cohort included about 30 000 radiologists who are currently younger than 70 years, which suggests that the cohort is quite complete. Radiologists are also unlikely to have been misclassified as psychiatrists or vice versa. Lack of data on confounding factors, such as smoking, could have biased our results in either direction. Mortality rates from chronic obstructive pulmonary disease were significantly lower in the radiologists than in the psychiatrists who graduated before 1940 (RR = 0.48; 95% CI: 0.25, 0.94), which suggests that smoking rates are lower in this group, which probably biased smoking-related mortality risks toward the null, particularly lung cancer. Lower smoking rates in radiologists than psychiatrists were also reported in the survey of the British Doctors Study in 1951 and 1966 (31). There are few medical specialties now that have no occupational radiation exposure, which is why psychiatrists were selected as the comparison. As with an earlier study of psychiatrists in the United States, we found higher death rates from suicide, accidents, and human immunodeficiency virus among psychiatrists compared with radiologists (32). As noted earlier, this may have biased results for NHL toward the null. Finally, even in this study that included the majority of U.S. radiologists who practiced in the last century there were too few women to study their mortality rates in detail. In addition, very few female radiologists worked during the early period, when exposures were likely highest.

There have been dramatic improvements in radiation protection since the earliest radiologists started practicing, including general lead shielding of equipment, personal use of lead aprons and glasses, and use of room shields (3). Early fluoroscopy procedures were likely a common and important source of radiation exposure to the radiologists who were practicing before 1940 (3). Decreases in the maximum permissible occupational dose have also occurred (33), and changes in radiation protection have changed the organs that received the highest radiation exposure. Early radiologists had high skin doses to hands and arms, used no personal protection garments, and received whole-body exposure from unshielded x-ray tubes (3). Current radiologists routinely wear lead or lead-equivalent aprons when performing fluoroscopy and may wear thyroid shields and leaded eyewear as well. The development of sensitive film badge monitors and government-required monitoring of medical radiation workers, along with a series of standards for radiation protection, also contributed to notable decreases in occupational radiation exposures, as borne out by survey data (11–14). Finally, there have been substantial changes in practice, with a shift toward radiologic technologists performing radiologic examinations rather than radiologists (3). Radiologists now receive radiation doses almost exclusively from fluoroscopy and some nuclear medicine procedures. The mean annual doses for radiologists in the United Kingdom decreased from 5 mGy in 1964 to 0.5 mGy in 1984, and the mean annual doses for radiologists in the United States from 1972 to 1978 ranged from 3.6 to 0.7 mGy (34). Exposures to physicians have increased in certain medical specialties in which fluoroscopically guided interventions are performed routinely, however, and these physicians, including interventional radiologists, are the subject of a separate investigation (3).

In conclusion, the excess risk of acute myeloid leukemia and/or myelodysplastic syndrome in radiologists compared with psychiatrists who graduated before 1940 is likely due to higher occupational radiation exposures. Excess risks of skin cancer, NHL, and cerebrovascular disease mortality in these earliest radiologists were observed. Low-dose radiation exposure is not an established cause of these cancers, but these findings warrant further investigation to test this possibility. Occupational radiation doses have been reduced substantially, and we found no evidence of excess mortality in U.S. radiologists who graduated from medical school after 1940, possibly because of increased radiation protection and/or lifestyle changes.

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