Special Review

Cancer Risks among Radiologists and Radiologic Technologists: Review of Epidemiologic Studies[1]

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Abbreviations:
SIR = standardized incidence ratio
SMR = standardized mortality ratio

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Radiologists and radiologic technologists were among the earliest occupational groups exposed to ionizing radiation and represent a large segment of the working population exposed to radiation from human-made sources. The authors reviewed epidemiologic data on cancer risks from eight cohorts of over 270 000 radiologists and technologists in various countries. The most consistent finding was increased mortality due to leukemia among early workers employed before 1950, when radiation exposures were high. This, together with an increasing risk of leukemia with increasing duration of work in the early years, provided evidence of an excess risk of leukemia associated with occupational radiation exposure in that period. While findings on several types of solid cancers were less consistent, several studies provided evidence of a radiation effect for breast cancer and skin cancer. To date, there is no clear evidence of an increased cancer risk in medical radiation workers exposed to current levels of radiation doses. However, given a relatively short period of time for which the most recent workers have been followed up and in view of the increasing uses of radiation in modern medical practices, it is important to continue to monitor the health status of medical radiation workers.
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Radiologists and radiologic technologists are among the earliest occupational groups exposed to radiation. It was the observation of the earliest radiologists that led to the recognition of radiation-induced skin cancer—the first solid cancer linked to radiation—in 1902 (1). In the 1940s and 1950s, excess mortality from leukemia among radiologists was recognized (2–4), and this, together with the rising concern about the effect of chronic radiation exposure, led to, among others, two landmark studies of radiologists—one in the United Kingdom (5) and the other in the United States (6).

Today, a large number of professional and technical personnel in medicine, dentistry, and veterinary medicine are exposed to radiation while administering various radiologic procedures—namely, diagnostic, therapeutic, interventional, and nuclear medicine procedures. New procedures are continuously introduced in the field of radiology. It is estimated that there are 2.3 million medical radiation workers worldwide—half of the entire work force that is exposed to human-made sources of radiation (7). Other radiation workers include those employed in the many stages of the commercial nuclear fuel cycle (800 000), in various industrial applications (700 000), and in defense activities (420 000) (7). It is important to evaluate potential health risks in such a large occupational segment of the population to ensure adequate radiologic protection.

The cancer risk associated with radiation exposure has been widely studied and documented. To date, the most important information on quantitative estimates of radiation-related cancer risk is derived from the long-term follow-up studies of the Japanese survivors of the atomic bomb blasts (7–9). However, the atomic bomb data are based on a single acute radiation exposure, while there is a relative paucity of comparable epidemiologic data on cancer risk from the chronic or fractionated exposures at low-to-moderate radiation doses that are more common in the workplace. Much information on the effects of chronic exposures has been obtained from studies of patients irradiated for medical reasons, but their exposures generally are at high dose rates and are directed to localized anatomic regions. In contrast, medical radiation workers typically are exposed to low doses

ESSENTIALS

- *High radiation exposure among early medical radiation workers resulted in excess risks of leukemia and cancers of the skin and, in women, breast.*
- *No excess cancer risk is evident among more recent workers.*
- *Marked improvements in radiation protection practices in recent times have led to a reduction in occupational exposures and cancer risks.*
- *Continued follow-up is necessary because recent workers are still young and have experienced different types of exposures from use of new radiologic procedures.*

at low dose rates to large parts of the body, which allows the assessment of cancer risks for many organs and tissues. Studies of medical radiation workers are, however, hampered by a lack of information on individual doses in most cases. Furthermore, some interventional radiologists and radiation therapists could have received very high doses.

A series of studies have been or are being conducted of nuclear industry radiation workers. Because nuclear power came into practical use when radiologic protection measures were already much improved, nuclear industry workers are generally exposed to radiation at lower doses than were the early medical radiation workers. A major limitation of the nuclear worker studies is the insufficient statistical power to enable detection of a low cancer risk associated with exposure at a very low dose, yet excess risks for leukemia and multiple myeloma have been noted in some nuclear worker populations (10,11).

In a review of the literature, we identified eight major cohort studies of radiologists, radiologic technologists, and other medical radiation workers. We herein evaluate the epidemiologic data on cancer risks among medical radiation workers and consider the usefulness of these data for the assessment of risks associated with chronic radiation exposure at low to moderate doses.

COHORTS

Through a MEDLINE search, references listed in published articles, and personal contacts with investigators, we identified eight major cohorts of medical radiation workers: three from the United States and one each from the United Kingdom, Denmark, China, Japan, and Canada. These cohorts are briefly described in the following paragraphs. The first two cohorts include radiologists; the remaining six are predominantly radiologic technologists or other medical workers.

The study of U.S. radiologists, reported by Matanoski et al (12–15), included a cohort of about 6500 radiologists and three cohorts of other physician specialists. This study was an extension of an original smaller cohort of radiologists established by Seltser and Sartwell (6,16). Radiologists who joined the Radiological Society of North America between 1920 and 1969 constituted the exposed-to-radiation group, while members of other medical specialties, who presumably were not exposed to radiation, served as the comparison groups. The latter groups included internists (members of the American College of Physicians) and otolaryngologists and ophthalmologists (members of the American Academy of Ophthalmology and Otolaryngology). The subjects were all men identified from the membership roster of each professional society, and they were followed up for mortality from 1920 through 1969—almost 50 years. A mortality study (17) in another cohort of about 8000 U.S. radiologists (members of the American College of Radiology) is not included in this review because the analysis grouped cancers and noncancer diseases in large categories and because a portion of the study population likely overlapped with the population of Matanoski et al (12,13).

An older but smaller cohort of about 2700 UK radiologists was an extension of the original cohort established by Court Brown and Doll (5) in the mid 1950s. The original cohort included male radiologists who registered with various radiologic societies in the United Kingdom between 1897 and 1954; they were followed up through 1957 and later through 1977 (18). The cohort members were followed up for mortality by using a variety of methods, including identification through the National Health Service Central Register (18). The cohort was extended to include an additional 1352 radiologists registered between 1955 and 1979. The latest mortality follow-up through 1997 represents 100 years of observation (19).

The cohort of U.S. radiologic technologists is the largest of all medical radiation worker cohorts studied. Approximately 146 000 radiologic technologists were followed up for mortality through 1990 (20) and more recently through 1997 (21). The cohort included all technologists certified for at least 2 years by the American Registry of Radiologic Technologists between 1926 and 1982. In contrast to other cohorts, especially that of radiologists, this cohort was predominantly female (73%). A subset of the cohort (about 90 000) responded to a mail questionnaire in 1983–1989 that elicited information on health status, radiologic work history, and disease risk factors (22). A second mail survey was conducted in 1993–1998 to obtain additional information on health status and potential risk factors (23).

Another, much smaller, cohort of radiologic technologists in the United States included 6500 men trained as U.S. Army x-ray technologists during World War II. These technologists, who were alive in 1946, together with a comparison group of medical laboratory and pharmacy technologists, were first followed up for mortality through 1963 (24) and later through 1974 (25) by means of searches of the files of the Veterans Administration, to which virtually all deaths of veterans were reported.

The cohort of Chinese medical x-ray workers included both radiologists and radiologic technologists but were referred to as diagnostic x-ray workers since, in China, there was little distinction between those two professions (26). A total of 27 000 diagnostic x-ray workers were identified from employment records in major hospitals in 24 provinces in China between 1950 and 1980. Other physicians who did not use x-ray equipment and who worked in the same hospitals during the same period constituted the comparison group. Incident cancers were ascertained by reviewing hospital records from 1950 through 1980 (26), 1985 (27), and, most recently, 1995 (28). Radiation doses were recently estimated from a random sample of 14% of the cohort (28). About 80% of the cohort members were men.

The Danish cohort of radiation therapy workers included a mixture of miscellaneous professions: nurses (42%), physicians (17%), technicians (5%), and other workers (36%) for whom radiologic monitoring data were available (29). Composed of a large proportion of nurses, this cohort was predominantly female (82%). The cohort included a total of 4100 subjects who worked between 1954 and 1982 in radiation therapy departments at two hospitals in Denmark. Incident cancers were identified through linkage to

TABLE 1
Selected Characteristics of Eight Cohorts of Medical Radiation Workers

Cohort*	Cohort Size: Total No. of Members	Cohort Size: No. of Women	Years First Worked	Follow-up	Completeness of Mortality Follow-up (%)†
U.S. radiologists (15)	6500	0	1920–1969‡	1920–1969	97
UK radiologists (19)	2700	0§	1897–1979‡	1897–1997	99
U.S. technologists (21)	146 000	106 800	1926–1982‡	1926–1997	99
U.S. Army technologists (24)	6600	0	Early 1940s‡	1946–1974	NA
Chinese x-ray workers (28)	27 000	5400	Before 1950 to 1980‖	1950–1995	NA
Danish radiation therapy workers (29)	4200	3400	1954–1982‡	1968–1985	NA
Japanese technologists (31)	12 200	0	1918–1971#	1969–1993	98
Canadian radiation workers (33,34)	73 100	46 800	Before 1950 to 1983‡	1951–1987	NA
Total	278 300	162 400			

* Numbers in parentheses are reference numbers.
† NA = not available.
‡ Assumed to be either years in which workers were certified or registered (U.S. and UK radiologists, U.S. technologists) or trained as U.S. Army radiologic technologist or in which radiation dose was first monitored (Danish and Canadian cohorts).
§ Cohort included 300 women, but they were excluded from the analyses.
‖ Determined from employment records.
\# Years first worked were those of an older subcohort of Japanese technologists, including 3461 technologists born in 1933 or before (32).

the Danish Cancer Registry for the period 1968–1985. Data on radiation doses were available through personal monitoring with film dosimeters after 1954.

The Japanese cohort of radiologic technologists was an extension of the original cohort established by Aoyama et al (30). The cohort included 12 000 male technologists who were identified from all radiologic technologists licensed through 1975 and born in 1950 or earlier (31). Mortality from 1969 through 1993 was ascertained by using the unique Japanese national family registry system (the *koseki*). Mortality for the technologists was compared with that for Japanese men and also with that for subsets of men employed in all occupations or in technical and professional occupations. Because work history or radiation dose data were not available (32), an internal comparison was made between two birth-year cohorts: the earlier birth cohort (born before 1933), who presumably had higher radiation exposures, versus the later birth cohort (born after 1933).

The Canadian cohort of radiation workers included 206 000 workers, of whom 73 000 were medical workers (33). More than 60% of the medical radiation workers in this cohort were women (Ashmore JP, written communication, 2000; Sont WN, written communication, 2001). Cohort members registered in the National Dose Registry of Canada between 1951 and 1983 were followed up for mortality, while the 191 000 workers registered between 1969 and 1983 were included in the incidence study (34). Radiation dose data based on individual monitoring were obtained by means of linkage to the National Dose Registry. Mortality and cancer incidence were ascertained through linkage to the Canadian Mortality Data Base and the Canadian Cancer Data Base, which is a nationwide cancer reporting system. Published data did not distinguish medical from nonmedical radiation workers.

These cohorts together represent more than 270 000 medical radiologic workers (Table 1). Radiologic technologists typically began their career when they were aged early 20s to late 30s (20,28), whereas radiologists joined specialty societies at somewhat older ages, usually between their mid-30s and mid-40s (12,19). While most of the cohorts are exclusively or predominantly male, the U.S. technologists and Canadian radiation workers include large numbers of women—106 000 and 46 000 women, respectively. These two cohorts, together with the Chinese and Danish cohorts with several thousand women, offer the opportunity for providing female cancer risk information not available from other occupational radiation populations, which are predominately male (eg, nuclear industry workers). Because of the availability of professional and specialist society membership records, mortality follow-up of medical radiation workers has been nearly complete (more than 97%) in all studies. The UK radiologists have been followed up for 100 years with virtually complete lifetime follow-up of the 696 earliest radiologists (first registered before 1936) (19). In addition, cancer incidence data were obtained for four cohorts by means of either linkage to nationwide cancer registries (Danish radiation therapy workers and Canadian radiation workers), review of medical records at the hospital where each subject worked (Chinese x-ray workers), or self-reported cancer diagnoses from responses to mail questionnaires (U.S. technologists).

Radiation Exposure

These cohorts represent a valuable source of information obtained from a large number of people who worked over several decades during which modern radiology and radiologic protection have evolved. The following brief account of the historical development of radiation safety standards for radiation workers in the United States and other Western countries illustrates the remarkable improvement in radiologic protection and the concomitant reduction in exposure during the past 60 years.

During the several years after the discovery of x-rays in 1895, radiologists were exposed to such high radiation doses that dermatitis and other radiation-induced injuries were common (35). The first radiologic protection standard for occupational exposure was introduced in 1902 (36); this standard was equivalent to 0.1 Gy per day (30 Gy per year!) and was not based on biologic data but rather on the lowest observable exposure to radiation, that is, fogging of a photographic plate. Many of the UK radiologists (1897–1920 subcohort) began their careers as radiologists during these early years.

In the mid-1920s, with accumulating information on the cancer and cell-killing effects of x-rays, the American Roentgen Ray Society recommended a tolerance dose of one-hundredth of an erythema dose per month for radiation workers (36), which was a 10-fold reduction from the earlier recommendation of one-tenth of an erythema dose per month (the erythema dose was estimated to be about 0.6 Sv). An important turning point was the year 1928, which saw the adoption of the roentgen unit and the creation of the International Advisory Committee on X-Ray and Radium Protection—the predecessor of the International Commission on Radiological Protection. The U.S. representative, returning from the first international congress meeting, set up the U.S. Advisory Committee on X-ray and Radium Protection, which proposed the first formal standard of 0.1 R (0.0258 mC/kg) per day (0.3 Sv per year) (37). The earliest subcohort (1920–1939) of U.S. radiologists worked during this period. Authors of one study (38) estimated that radiologic workers during 1920–1930 could have been exposed to 100 R (2.58×10^{-2} C/kg) per year (1 Sv per year).

The conditions improved in the ensuing decades. In a survey in 1940, a large number of U.S. hospitals reported an average daily exposure of 0.005 R (0.0013 mC/kg)—roughly equivalent to 0.01 Sv per year—with the maximum exposure of 0.1 R (0.0258 mC/kg) per working day (39). In the early 1950s, the usual weekly dose received by radiologic personnel at the Cleveland Clinic (Ohio) was from more than 0.1 R (0.0258 mC/kg) to a maximum of 0.3 R (0.0774 mC/kg) (>0.05 to ≤ 0.15 Sv per year) (40). Large numbers of the U.S. technologists (20,22) and Canadian radiation workers (33,34) were employed during the period of 1940–1950.

In 1957, the International Commission on Radiological Protection recommended a dose limit of 0.05 Sv per year (36), which led to much lower levels of exposure. Most recently, the 1990 International Commission on Radiological Protection recommendation introduced a new occupational dose limit of an average of 0.02 Sv per year averaged over a 5-year period, with the further provision that the dose should not exceed 0.05 Sv in any single year (8).

It was not until the 1950s or later that routine film-badge (dosimeter) monitoring of radiation doses for medical radiation workers began to be introduced in various countries (14,22,28,29,31,33). Therefore, only limited individual measurement data were available for most of the cohorts reviewed here. Individual cumulative radiation doses were estimated from film-badge data available in 1954 or later for the Danish radiation therapy workers (29) and in 1951 or later for the Canadian radiation workers (33,34). In the Danish workers, the mean cumulative radiation dose after 1954 was 18.4 mSv, with 17% of the workers having zero exposure and 9% having 50 mSv or higher exposure. In the Canadian mortality study, the mean radiation dose received between 1951 and 1987 was estimated to be 6.3 mSv for all the radiation workers, 3.8 mSv for medical workers, and 0.3 mSv for dental workers (33). Few records were available in the Canadian National Dose Registry prior to 1950.

Cancer Risks

The standardized mortality ratio (SMR) and standardized incidence ratio (SIR), commonly used in occupational studies, are the ratio of the number of deaths or incident cases, respectively, observed in the study population to the comparable number expected if the study population had the same rate structure as did the standard population (41). The SMR and SIR are not ideal measures of risk because the population being studied, especially a working population, can differ substantially from the general population. Use of an occupational population as a control group—for example, comparison of doctors in one specialty with those in another specialty—is often preferable. However, the comparison group can also differ from the study group in ways other than the risk factors of interest. Comparison of SMRs or SIRs from different studies is further limited because of heterogeneity among study cohorts in terms of data quality, length of follow-up, other exposures, and lifestyle factors. However, comparisons among different studies on the basis of SMRs and SIRs when other methods are not possible still allow us to discern important similarities and differences. An advantage of a review of many studies with different populations and study methods is that the consistency of results can be evaluated.

The SMRs and SIRs for all causes of death, all cancers, and leukemia from the eight cohorts are presented in Table 2, which includes unpublished data from the Canadian radiation workers (Ashmore JP, personal communication, 2000; Sont WN, personal communication, 2001). The SMR for all causes was less than 1 in most cohorts. A low SMR for all causes in occupational studies is likely to be due to a "healthy-worker effect." This effect commonly occurs because workers are often healthier than the general population, in that the latter includes ill and disabled individuals who may not be employed. The influence of the healthy-worker effect varies from one occupational cohort to another (42) but may be more pronounced in medical radiation workers who have better access to medical care than do others and may have a healthier lifestyles (eg, smoke less, eat better).

The impression that the healthy-worker effect may be involved is strengthened by two observations: *(a)* The all-cancer SMR for the U.S. Army technologists was about 1 compared with the SMR of other medical laboratory and pharmacy technologists, and *(b)* the deficit all-cancer SMR was reduced when medical practitioners (UK radiologists study) or all professional and technical workers (Japanese technologists study) were used as the comparison populations instead of the general populations. In the UK radiologist cohort, the SMR for all causes was less than 1 even when compared with that of the most relevant peer group, medical practitioners, and this was considered likely in part because of the healthy-worker effect not yet having completely diminished among the most recent group of radiologists (19,43). This again emphasizes the care needed in using the SMR or SIR as a measure of risk. Nevertheless, the significantly elevated SMR of 1.38 for all cancers in the U.S. radiologists (compared with other physician specialists) and that of 1.16 in the UK radiologists (compared with medical practitioners) are likely more accurate than results of other studies with a general population as the comparison population in approximating the magnitude of the excess for these cohorts. A significantly elevated SIR for all cancers was found for male Chinese x-ray workers (compared with nonradiology workers) and female U.S. technologists (compared with data from the U.S. Surveillance, Epidemiology and End Results program). The significantly elevated SMR or SIR of 1.75–2.29 for leukemia found in the U.S. radiologists, Japanese technologists, and male Chinese x-ray workers (Table 2) also suggests a radiation-related excess in these populations.

A statistically significant SMR or SIR for a study group does not demonstrate a causal relationship. To establish causality, further evidence is necessary, including demonstration that the findings are consistent among similar studies involving different groups of subjects.

More important is the analysis of the relationship between exposure (dose) and cancer risk (response), which is essential for risk assessment. In the absence of individual dose estimates, many investigators have used proxy measures that

TABLE 2
SMRs and SIRs for All Causes of Death, Cancers, and Leukemia for the Reported Follow-up in Eight Cohorts of Medical Radiation Workers

Cohort and Sex*	Comparison Population	All Causes	All Cancers	Leukemia
		SMR†		
U.S. radiologists (14)‡	Physician specialists			
Male		NA	1.38 (NA)§	2.01 (NA)§
UK radiologists (19)	UK population			
Male		0.77 (1042)§	0.73 (228)§	NA
UK radiologists (19)	Medical practitioners			
Male		0.92 (1042)§	1.16 (228)§	NA
U.S. technologists (21)	U.S. population			
Female		0.76 (7567)§	0.86 (2558)§	0.92 (98)
Male		0.76 (5057)§	0.73 (1137)§	0.95 (60)
U.S. Army technologists (24)	Medical laboratory and pharmacy technologists			
Male		1.06 (289)	1.05 (55)	1.25 (8)
Japanese technologists (31)	Japanese population			
Male		0.65 (1097)§	0.81 (435)§	1.31 (20)
Japanese technologists (31)	Japanese professional and technical workers			
Male		0.88 (1097)§	0.98 (435)§	1.75 (20)§
Canadian radiation workers‖	Canadian population			
Female		0.61 (671)§	0.66 (256)§	0.54 (9)§
Male		0.51 (1153)§	0.56 (301)§	0.77 (17)
		SIR#		
U.S. technologists (23)	U.S. SEER program**			
Female		NA	1.07 (2408)††	1.12 (48)
Male		NA	0.94 (884)††	1.04 (27)
Chinese x-ray workers (28)	Nonradiology medical workers			
Female		NA	1.02 (157)	1.74 (8)
Male		NA	1.24 (679)§	2.29 (36)§
Danish radiation therapy workers (29)	Danish population			
Female and male		NA	1.07 (163)	0.70 (2)
Canadian radiation workers§§	Canadian population			
Female		NA	0.86 (869)††	0.44 (10)§
Male		NA	0.64 (561)††	0.57 (16)§

* Number in parentheses is reference number.
† Value in parentheses is number of deaths. NA = not available.
‡ Data for Radiological Society of North America members in 1920–1939.
§ $P < .05$.
‖ Unpublished data (Ashmore JP, 2000).
Value in parentheses is number of cases. NA = not available.
** SEER = Surveillance, Epidemiology and End Results (National Cancer Institute).
†† SIR for all cancers except nonmelanoma skin cancers. $P < .05$.
§§ Unpublished data (Sont WN, 2001).

reflect historical changes in radiation exposure among workers. This was done by dividing the cohort into subcohorts according to the calendar year of certification or registration for professional activities (UK radiologists, U.S. radiologists, U.S. technologists), the calendar year first worked in the profession (U.S. technologists, Chinese x-ray workers), or the birth year (Japanese technologists). Some authors have used work duration as a proxy measure, but this may not be a useful surrogate for cumulative exposure unless knowledge of historical changes in exposure is incorporated in analyses. In the Chinese x-ray worker study, occupational doses were estimated for a subset of the cohort by using phantom simulation for past working conditions and detailed work history obtained at interviews (44). Average cumulative doses were estimated to be 0.551 Gy for the early subcohort (first employed before 1970) and 0.082 Gy for the later subcohort (first employed from 1970 to 1980). In the Danish and Canadian studies, information on measured doses was used, but some of the cohort members were exposed to radiation before dose measurement was introduced. Analyses based on incomplete dose data will likely bias the risk estimate, and ignoring high doses in the early years may lead to underestimation of doses and, hence, overestimation of the risk per unit dose.

Leukemia and Lymphomas

SMRs and SIRs for leukemia and selected sites of cancer according to proxy measures of radiation exposure or measured doses are presented in Table 3. In most cohorts, the SMRs or SIRs for leukemia were increased in the earliest subcohorts, whether defined by year of registration, certification, or birth (Table 3). Significantly elevated mortality or incidence of leukemia was observed in the 1920–1939 subcohort of the U.S. radiologists (SMR = 2.01), the 1897–1920 subcohort of the UK radiologists (SMR = 6.15) and the pre-1970 Chinese x-ray workers (SIR = 2.37), while leukemia mortality was not significantly elevated among workers employed in later years. In the U.S. radiologist study, leukemia mortality in the 1920–1929 subcohort of radiologists was nine times higher than that in the comparable subcohort of physi-

TABLE 3
SMRs and SIRs for Selected Sites of Cancer according to Exposure Subcohorts among Six Medical Radiation Worker Cohorts

Cohort and Subcohort*	Comparison Population	Exposure Measure	Stomach	Colon†	Liver	Pancreas	Lung‡	Breast	Skin	Leukemia	Lymphoma§
			SMR‖								
U.S. radiologists (14)	Physician specialists	Year of registration									
1920–1939			1.01 (NA)	1.25 (NA)	1.45 (NA)	0.97 (NA)	0.96 (NA)	NA	3.38 (NA)#	2.01 (NA)#	2.73 (NA)#
1940–1969			1.33 (NA)	0.60 (NA)	0.56 (NA)	0.72 (NA)	1.22 (NA)#	NA	2.41 (NA)	1.00 (NA)	0.41 (NA)
UK radiologists (18)	Social class I	Year of registration									
1897–1920			1.20 (7)	1.28 (9)	NA	3.23 (6)#	2.18 (8)#	NA	7.79 (6)#	6.15 (4)#	NA
1921–1954			0.68 (6)	0.61 (6)	NA	0.84 (4)	0.97 (23)	NA	1.96 (2)	1.54 (4)	NA
UK radiologists (19)	Social class I	Year of registration, excluding deaths < 20 y after registration									
1897–1920			1.38 (5)	1.27 (6)	NA	3.88 (5)#	2.46 (7)	NA	4.35 (2)	2.50 (1)	0.00 (0)
1921–1935			1.29 (5)	0.84 (4)	NA	0.87 (2)	1.06 (11)	NA	4.55 (2)	2.70 (3)	0.00 (0)
1936–1954			0.97 (5)	0.51 (4)	NA	0.97 (4)	0.74 (14)	NA	0.00 (2)	1.75 (4)	2.93 (6)#
1955–1979			0.60 (1)	0.63 (2)	NA	0.62 (1)	0.00 (0)	NA	0.00 (2)	1.16 (1)	2.75 (3)
All post-1920			1.03 (11)	0.63 (10)	NA	0.87 (7)	0.70 (25)	NA	1.09 (2)	1.88 (8)	2.41 (9)#
U.S. technologists (20)	U.S. population	Year of certification									
1926–1939			NA	NA	NA	NA	0.72 (34)	1.53 (78)	NA	1.26 (16)	NA
1940–1949			NA	NA	NA	NA	0.76 (106)	1.06 (97)	NA	1.00 (22)	NA
1950–1959			NA	NA	NA	NA	0.83 (193)	0.91 (127)	NA	0.71 (22)	NA
1960–1982			NA	NA	NA	NA	0.61 (96)	0.83 (123)	NA	0.97 (43)	NA
Japanese technologists (31)	Japanese population	Birth year									
1897–1933			0.64 (79)	1.32 (28)	0.83 (52)	0.83 (20)	0.62 (50)	NA	1.58 (2)	1.55 (14)	1.48 (15)
1934–1950			0.70 (19)	1.20 (7)	0.81 (13)	0.99 (5)	0.45 (5)	NA	0.00 (0)	0.95 (6)	0.56 (2)
			SIR**								
Chinese x-ray workers (28)	Nonradiology medical workers	Year first worked									
Before 1970			1.01 (66)	NA	1.39 (115)#	NA	1.10 (108)	1.34 (29)	4.31 (16)#	2.37 (33)#	NA
1970–1980			1.63 (36)#	NA	0.85 (40)	NA	1.57 (43)#	1.33 (17)	2.74 (2)	1.73 (11)	NA
Danish radiation therapy workers (29)	Danish population	Measured dose									
0 mSv			NA	NA	NA	NA	2.66 (2)	1.98 (5)	0.62 (1)	0.00 (0)	0.00 (0)
0.01–5.0 mSv			NA	NA	NA	NA	1.61 (6)	0.81 (9)	0.72 (5)	1.09 (1)	0.00 (0)
5.01–50.0 mSv			NA	NA	NA	NA	0.78 (4)	1.64 (21)	1.90 (14)	0.98 (1)	0.00 (0)
>50.0 mSv			NA	NA	NA	NA	1.20 (4)	1.17 (9)	1.13 (5)	0.00 (0)	1.35 (1)

* Number in parentheses is the reference number.
† Cancer of intestine in UK radiologists.
‡ Respiratory cancer in Danish radiation therapy workers.
§ Lymphosarcoma in U.S. radiologists; non-Hodgkin lymphoma in UK radiologists.
‖ Mortality studies. Value in parentheses is number of deaths. NA = not available.
# $P < .05$. Statistical significance was tested by means of heterogeneity of SMRs among three occupational groups in U.S. radiologist study and by means of differences of SMRs or SIRs from unity in the other studies.
** Incidence studies. Value in parentheses is number of cases. NA = not available.

TABLE 4
Relative Risk of Mortality due to Selected Cancers according to Number of Years Worked in Specified Calendar Year Periods among U.S. Radiologic Technologists

Calendar Year Period of Employment	No. of Years Worked in Each Calendar Year Period*			*P* Value for Trend†
	0 (referent category)	1–4	5 or More	
Breast cancer				
Before 1950	1.0 (37)	2.17 (35)‡	2.08 (29)‡	.018
1950–1959	1.0 (57)	1.18 (67)	1.08 (63)	NS
1960–1969	1.0 (63)	1.06 (79)	0.97 (106)	NS
1970–1979	1.0 (81)	0.75 (34)	0.76 (143)	NS
Lung cancer				
Before 1950	1.0 (95)	0.86 (57)	0.72 (53)	NS
1950–1959	1.0 (64)	0.97 (73)	1.04 (130)	NS
1960–1969	1.0 (70)	0.79 (43)	0.92 (173)	NS
1970–1979	1.0 (90)	1.14 (42)	0.86 (156)	NS
Leukemia§				
Before 1950	1.0 (5)	1.46 (3)	4.95 (7)	.05
1950–1959	1.0 (14)	0.27 (3)	0.54 (10)	NS
1960–1969	1.0 (10)	1.47 (9)	1.03 (17)	NS
1970–1979	1.0 (4)	1.76 (3)	3.20 (29)	NS

Source.—Reference 21.
* Data are relative risk, with number of deaths in parentheses.
† NS = not significant.
‡ $P < .05$.
§ Excluding chronic lymphocytic leukemia.

cians who were not exposed to radiation (13).

Although previous data from the U.S. technologists (Table 3) did not show a significant association between leukemia risk and year first certified, the latest data, in Table 4, show that mortality from leukemia (excluding chronic lymphocytic leukemia, which has not been associated with radiation exposure) increased with increasing duration of employment as a radiologic technologist before 1950 (21). Thus, data from four of the cohorts provided statistically significant evidence of excess leukemia risk among medical radiation workers who were employed during early calendar year periods.

The data from the Chinese x-ray worker study also suggested that the relative risks of leukemia were especially high among those who began working before 20–25 years of age and among those at an attained age before 40 years (28). This is consistent with the atomic bomb survivor data, which showed a higher leukemia risk associated with younger age at exposure (45). While the excess leukemia risk among the atomic bomb survivors decreased with time after the single exposure, the excess leukemia mortality in the post-1920 cohort of UK radiologists, who had chronic radiation exposure, persisted more than 20 years after certification (19).

The U.S. radiologists data in Table 3 show excess mortality from lymphoma in the 1920–1939 subcohort. This excess was due primarily to the large excess in the 1930–1939 subcohort, but excess mortality also was evident in the later 1940–1949 subcohort (13). In similar fashion, excess lymphoma mortality began to emerge in the post-1920 subcohort of the UK radiologists, with significantly higher-than-expected mortality being observed in the 1936–1954 subcohort (Table 3). The lack of excess lymphoma mortality among the earliest subcohorts of these radiologists is not consistent with the radiogenic origin of the observed excesses, but how these patterns relate to radiation or other exposures may be worthy of further study.

Solid Cancers

The data from the UK radiologists showed a modest nonsignificant excess SMR for stomach cancer in the 1897–1920 worker cohort followed by a gradually decreasing SMR in more recent workers (Table 3). The Japanese and Chinese data showed an opposite pattern: The SMRs or SIRs decreased in the earlier subcohorts; the SIR among the later subcohort (1970–1980) of Chinese x-ray workers was significantly elevated (Table 3). SMRs for colon cancer tended to be higher among early subcohorts in the UK and U.S. radiologists and in the Japanese technologists, but none were statistically significantly elevated.

The SMRs for liver cancer showed inconsistent patterns between the U.S. radiologists and Japanese technologists. Mortality data for liver cancer, however, are subject to considerable misclassification, because the reported causes of death on death certificates include a large proportion of metastases of cancer that originated at other sites. Incidence data are better for the assessment of liver cancer risk, and so the significantly elevated SIR for liver cancer among the earlier (pre-1970) Chinese x-ray workers is particularly important. The extremely high SMR for cancer of the pancreas in the 1897–1920 cohort of UK radiologists was not replicated in the other exposed cohorts, so this is likely to be a chance finding.

Significantly elevated mortality from lung cancer in the 1897–1920 subcohort of the UK radiologists in the earlier analysis by Smith and Doll (18) was no longer significant when the analysis was limited to deaths occurring 20 or more years after registration (19). An opposite pattern—namely, a higher SMR or SIR in the later subcohort—was observed in the U.S. radiologists and Chinese x-ray workers. These findings are difficult to interpret without information on smoking habits, which may have changed over the years in these populations.

Recent analysis of the mortality data from the U.S. technologist cohort demonstrated that the relative risk of breast cancer, after adjustment for known risk factors, was significantly increased among women first employed before 1940 (relative risk, 2.92) and from 1940 to 1949 (relative risk, 2.44) compared with that in women first employed in 1960 or later (21,46). Relative risk was significantly ($P < .05$) elevated among women who worked 1–4 years (relative risk, 2.17) and 5 or more years (relative risk, 2.08) before 1950, compared with that in women who never worked during that period, and the risk rose significantly with increasing number of years worked before 1950 ($P = .018$ for trend) (Table 4). These findings provide evidence of an excess breast cancer risk associated with occupational radiation exposure in these early technologists. In the Chinese x-ray workers and the Danish radiation therapy workers, no apparent exposure-response patterns were observed for breast cancer, but exposure was based only on duration of employment or incomplete dose data.

Excess skin cancer mortality was observed in the early radiologists in both the United States and the United Kingdom (Table 3). In the 1920–1929 U.S. radiologist subcohort, skin cancer mortality was reported to be 10 times higher than that for otolaryngologists (13). In the UK radiologists, excess skin cancer mortality in the 1897–1920 subcohort was confined to the first 20 years of follow-up. Skin cancer mortality was also increased, albeit not significantly, in the earlier birth cohort of the Japanese technologists. Incidence data are more relevant for mostly nonfatal skin cancers. The Chinese cohort data demonstrated significantly increased incidence of skin cancer among the earlier subcohort (ie, those who worked before 1970). Although the trend was not significant, skin cancer incidence increased with increasing measured dose among Danish radiation therapy workers (29). It should be noted that most of the Danish and Chinese cohort members began their radiologic careers a few decades later and possibly were exposed to much lower doses than were the earliest U.S. and UK radiologists.

A modest increase in melanoma risk among U.S. radiologic technologists was reported (data not presented in Table 3). This was based on internal cohort analyses of 207 incident melanoma cases, with adjustment for skin characteristics and residential sunlight exposure (47). Work as a radiologic technologist before 1950 conferred a nonsignificantly elevated 1.8-fold risk, on the basis of 15 cases with a significantly increasing trend associated with working 5 or more years before 1950 (48). An increased SIR for melanoma was found among the Canadian radiation workers (SIR = 1.16; 95% confidence interval: 1.04, 1.30) (34). The association with melanoma, however, was curiously limited to dental workers, a subset of the radiation workers who had the lowest recorded film-badge doses. Anecdotal evidence suggests that dental workers may have held bitewing film in patients' mouths during x-ray exams, resulting in particularly high exposure to the hands; however, since the anatomic locations of the melanomas were not reported, this hypothesis could not be evaluated.

COMMENTS

The most consistent observation resulting from this review is the increased leukemia risk observed in the early subcohorts of medical radiation workers. In the UK and U.S. radiologists, the excess leukemia risk was evident among those who first worked before or during the 1920s. However, the excess leukemia risk was not limited to radiologists who worked in the earliest period of radiologic practices. The UK radiologist data demonstrated increased mortality in post-1920 subcohorts. The analysis of the U.S. technologists data, with duration of work taken into account, showed the excess mortality risk associated with occupational exposure that occurred from the late 1920s to 1950 (21). The excess leukemia risk in the more recent pre-1970 subcohort of Chinese x-ray workers is notable but may not be surprising given the considerably higher average exposure (0.551 Gy) reported for this cohort of workers (28). The persistence of the leukemia risk seen in the latest UK radiologists follow-up data is consistent with the prolonged leukemogenic effect of radiation exposure at adult ages observed among the atomic bomb survivors (45).

The findings with regard to solid cancer were less consistent, but some conclusions may be drawn about several specific types of cancer. Excess skin cancer mortality observed in the earliest subcohorts of radiologists in the United States (14) and the United Kingdom (18) is in line with the historical observation by Frieben (1) of an elevated frequency of skin cancer among radiologists at the beginning of the past century. The skin cancers among the earliest radiologists were largely squamous cell carcinomas (48) and may have occurred as sequelae of chronic skin conditions caused by excessive radiation exposures. The relatively high case fatality rate associated with squamous cell carcinomas of the skin may have been reflected in excess mortality. In contrast, an excess risk of basal cell carcinoma, which is rarely fatal, has been seen among populations exposed to radiation at lower doses (7,48). It is, therefore, important to note the increased risk of skin cancer incidence among the Chinese and Danish workers, who began radiologic work much later than did the U.S. and UK radiologists. Unfortunately, these studies do not include information on histologic types or tumor location. Further studies of skin cancer incidence among these and other medical radiation workers are indicated.

Special attention should be given to specific locations and types of skin cancer, because they may be uniquely associated with specific radiologic practices such as handling of radioactive materials or holding of patients during procedures. Recent reports of excesses of malignant melanoma among radiologic technologists and other radiation workers (34,47) will require confirmation of the association with occupational exposures. The suggestive evidence of increased liver cancer risk in the Chinese x-ray workers is in line with the finding from the atomic bomb survivors (49). In the latter population, the radiation-associated liver cancer risk has been found to be modified by the presence of hepatitis infection (50). The findings for other cancer sites are varied and do not present any consistent patterns.

Medical radiation worker cohorts offer one of the few opportunities for obtaining direct observational evidence on health effects associated with chronic low-dose radiation exposures. The lack of data on individual doses, however, has prevented adequate quantification of risks or formal comparison of risks with those obtained from high-dose and high-dose-rate studies. The unavailability of dose estimates and the heterogeneity of study methods preclude a systematic and more informative evaluation, such as could have been performed in a meta-analysis. Currently, efforts are being made in several studies to estimate individual doses retrospectively. Reconstruction of doses before 1950 is most important because of the high level of exposure among the early workers, but this remains a challenge in most studies. Dose reconstruction has been attempted by using information on past working conditions, phantom modeling, mathematic models, and validation with other independent measures of exposure such as chromosomal aberration data for the Chinese x-ray workers (28). In the U.S. technologist study, archived dosimetry records are being used together with individual work histories and literature-based average annual dose estimates for early calendar years to estimate individual doses. Once dose reconstruction is completed in these studies, valuable quantitative dose-response data will be forthcoming.

By reviewing the currently available epidemiologic data, we conclude that occupational radiation exposures among early medical radiation workers resulted in excess risks of leukemia and also possibly a few other types of cancer. The excess cancer risks in this professional group largely resulted from high exposures experienced by workers employed during the periods of inadequate radiologic safety policies and practices. Marked improvements in radiologic protection practices in recent years have led to a reduction in occupational exposure and health risks. We found no clear evidence of an elevated cancer risk in any of the latest subcohorts of radiologists or technologists. It should be realized, however, that recent cohorts of radiologic workers have not been followed up as long as the earlier cohorts were. For example, most of the 1960–1982 subcohort of U.S. technolo-

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gists is yet to enter ages of increased background cancer risk. There is also some evidence that risks of certain cancers, notably skin cancer, may be increased among more recent medical radiation workers, and this may be related to specific or changing radiologic practices. The excess leukemia risk reported in nuclear industry workers exposed to very low radiation doses (10) indicates the need to continue to monitor leukemia risk in recent radiologic workers.

Radiation is used increasingly in modern medicine as numerous new radiologic procedures are introduced. The use of fluoroscopically guided diagnostic and interventional procedures has rapidly increased in the past few decades and has resulted in exposure of radiologic staff (51), and these exposures may be different from the exposures of early practitioners. While safe radiation practices currently are an assumed part of medical radiation work, the results reported in this review suggest that it is important to update the medical profession periodically and to continue follow-up of the medical radiation worker cohorts.

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