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100 years of observation on British radiologists: mortality from cancer and other causes 1897–1997

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Abstract. Radiologists and radiotherapists were one of the earliest occupational groups to be exposed to ionizing radiation. Their patterns of mortality provide information on the long-term effects of fractionated external radiation exposure. British radiologists who registered with a radiological society between 1897 and 1979 have now been followed-up until 1 January 1997, and the mortality experience examined among those who registered with a society after 1920, when the first radiological protection recommendations were published. The observed number of cancer deaths in those who registered after 1920 was similar to that expected from death rates for all medical practitioners combined (SMR=1.04; 95% CI 0.89–1.21). However, there was evidence of an increasing trend in risk of cancer mortality with time since first registration with a radiological society (p=0.002), such that in those registered for more than 40 years there was a 41% excess risk of cancer mortality (SMR=1.41; 95% CI 1.03–1.90). This is probably a long-term effect of radiation exposure in those who first registered during 1921–1935 and 1936–1954. There was no evidence of an increase in cancer mortality among radiologists who first registered after 1954, in whom radiation exposures are likely to have been lower. Non-cancer causes of death were also examined in more detail than has been reported previously. There was no evidence of an effect of radiation on diseases other than cancer even in the earliest radiologists, despite the fact that doses of the size received by them have been associated with more than a doubling in the death rate among the survivors of the Japanese atomic bombings.

Studies of human populations exposed to acute, high doses of ionizing radiation have proved valuable in assessing the link between radiation and cancer and have been used to derive quantitative estimates of risk. However, the applicability of these estimates to the assessment of risks following fractionated or low level exposures remains uncertain. It is appropriate, therefore, to study populations who have received such exposures in order to assess the resulting risks directly. Radiologists and radiotherapists were one of the earliest occupational groups to be exposed to external radiation and their patterns of mortality provide information on the long-term effects of exposure to repeated doses of radiation. Among the early radiologists the total accumulated doses were substantial, but more recently the doses were likely to have been much smaller.

In 1956 Court Brown and Doll set up a study to find out if British radiologists who had joined a radiological society before 1955 had suffered an increased risk of death from cancer attributable to their occupational radiation exposure. It was found that those who had registered with a radiological society before 1921, when the first radiation protection recommendations were published, did have a significantly increased risk of dying from cancer [1]. In 1981 Smith and Doll extended the follow-up of this cohort to 1 January 1977. By this time all those who had registered before 1921 had died and were found to have a death rate from cancer 75% (95% CI 34%–126%) higher than that of medical practitioners in general [2]. Among the radiologists registered after 1920 the total mortality from cancer was not significantly increased (5%, 95% CI −15% to 28%) compared with medical practitioners, but there was a suggestion of a progressive increase in risk with the number of years since first registration with a radiological society. The trend was just significant statistically with a one-sided test (p=0.04).

We have extended the follow-up of these British radiologists for an additional 20 years to examine further the cancer mortality of those joining a

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radiological society during 1921–1954, and have also expanded the study to include radiologists who registered with The Royal College of Radiologists between 1954 and 1979. The cohort consequently now includes all 2698 male radiologists who joined one of the main radiological societies in Britain between 1897 and 1979 and who are likely to have received a wide range of levels of radiation exposure. In this report the mortality experience of the cohort is presented with emphasis on the trend in cancer mortality with time since first registration with a radiological society. We have also examined the non-cancer causes of death in these radiologists in more detail than has been reported previously, as studies of the atomic bomb survivors in Hiroshima and Nagasaki have recently shown an increased mortality from circulatory, respiratory and digestive diseases related to radiation dose [3].

Methods

Study population and follow-up

The original cohort included 1338 male radiologists who registered with either the British Institute of Radiology or the Royal College of Radiologists between 1897 and 1954 and were resident in the UK or Ireland. Court Brown and Doll [1] and Smith and Doll [2] describe the original study population in detail. We have expanded the cohort by adding 1352 male radiologists who registered with the Royal College of Radiologists between 1955 and 1979 and were resident in the UK in their first year of registration. A further eight radiologists who joined the Royal College of Radiologists in 1954 but were missed in the original cohort were also included.

A variety of methods were used to identify the status of all radiologists at the end of follow-up, 1 January 1997. Identifying details (name, date of birth and last known address) obtained from the Royal College of Radiologists membership lists were sent either to the Office for National Statistics (ONS) or where appropriate to the Central Services Agency (CSA) in Belfast to obtain notifications of deaths, emigrations or current National Health Service Central Register (NHSCR) registration details.

If no notification of death or emigration had been received, study members were assumed to be alive and living in the UK on 1 January 1997 if they were listed with a UK address in the 1998 editions of either the Royal College of Radiologists Handbook or the Medical Directory. For study members whose status could not be confirmed by these sources we searched the previous editions of these publications or the Medical Register for their last contact address and, if it was in the UK, wrote to them personally asking for confirmation of their current address. If they were listed with a non-UK address they were assumed to have emigrated (if they subsequently returned to the UK they were not reintroduced into the study). The original cohort included study members resident in the Republic of Ireland. Follow-up for these study members could not be extended using the current methods. Individuals living in the Republic of Ireland at the end of the previous follow-up, therefore, were considered to have emigrated on that date (1 January 1977). If all the methods of follow-up failed then subjects were assumed lost to follow-up on whichever was the latest date out of the year they were last listed in the Royal College of Radiologists Handbook or the Medical Directory, their last posting date with the NHSCR, or 5 years before they were last listed in the Medical Register (as the register updates addresses only every 5 years).

Certified causes of death were obtained for the radiologists who had died and the underlying cause of death was coded according to the 9th Revision of the International Classification of Diseases and Causes of Death [4]. Cause of death could not be ascertained for 10 individuals who were known to have died. These deaths were included only in analyses of all causes of death.

300 female radiologists were also identified who had registered with a radiological society between 1955 and 1979. By the end of follow-up 31 had died, 55 had emigrated and 14 were lost to follow-up. The cohort is currently too small for further meaningful analysis.

Methods of analysis

The period of observation for each radiologist began on the date of first registration with a radiological society and ended with the date of death or emigration, loss to follow-up or 1 January 1997, whichever was earliest. For the purpose of comparing mortality with published death rates, follow-up was limited to the age of 85. This is because death rates for the general population are published by combining all those aged 85 years and over. In the general population the age structure of this open-ended age group may be very different to that of the radiologists and the death rates would not be comparable. It is also thought that the cause of death is recorded less accurately on death certificates for deaths over age 85: this would make comparisons for specific causes of death unreliable.

Mortality was analysed using standardized mortality ratios (SMRs), that is ratios of the numbers of observed deaths to the numbers expected in a specific comparison population. To calculate the expected number of deaths, the number of years of observation was divided into 5 year age groups (20–24, ..., 80–84 years) and calendar periods (1897–1905, 1906–1910, ..., 1986–1990, 1991–1996). The corresponding number of expected deaths was then calculated for each age/calendar period specific category using death rates for: (i) the general male population, (ii) social class I males and (iii) male medical practitioners. For each of these three comparison populations the total number of expected deaths was then calculated by summing over all age and calendar periods. Death rates for all causes of death and for circulatory, respiratory, external and other non-cancer causes of death in the general population of England and Wales were compiled using the ONS historic data files. For the periods from 1911–1916 to 1936–1940 death rates for all cancers and cancers of specific sites in the general population were taken from Case et al [5], for 1941–1996 rates were taken from the ONS historic data files and the rates for 1911–1916 were used for 1897–1910.

Death rates for medical practitioners and social class I males were not available directly but were estimated from the occupational mortality supplements published every decade by the Registrar General [6–12]. These supplements are based upon census information and provide estimates of SMRs for the major causes of death by occupation and social class compared with the general population rates. To estimate the death rates for social class I males and medical practitioners, the general population death rates were multiplied by these SMRs. Age-specific rates could be estimated for all causes of death and all cancers, circulatory, respiratory and external causes of death as these SMRs were published by age group for 20–24, 25–34, 35–44, 45–54, 55–64 and 65+ year olds. However, as the previous occupation of men who have retired is often poorly recorded in the national censuses we have assumed that the SMRs for men aged 55–64 years provide a better estimate than the published SMR for those aged 65+. For specific cancer sites the SMRs are published only by social class and only for all 20–64 year olds combined. Therefore estimated death rates for specific cancer sites for social class I males were estimated assuming the SMR was constant across all age groups. Further details of the computation of the mortality rates for social class I males and medical practitioners are given by Smith and Doll [2].

Individual dose information, in the form of dosimetry or surrogate measures such as number of years of registration, was not available. To assess the effect of the level of radiation exposure Smith and Doll subdivided the radiologists into three subgroups according to their year of first registration with a radiological society: pre-1921, 1921–1935 and 1936–1954. The divisions were chosen to reflect major changes in radiological protection recommendations and corresponded roughly to high, medium and low levels of exposure. In this report we have used the same classification and added a fourth group of post-1954 radiologists expected to have had even lower levels of exposure, following a further major revision of occupational dose recommendations by the International Commission on Radiological Protection [13].

The statistical significance of the SMRs and their 95% confidence intervals (CI) were calculated assuming that the number of observed deaths from any cause had a Poisson distribution and that the expected number of deaths was fixed. Exact 95% Poisson confidence intervals were calculated using Stata [14]. The Poisson trend statistic was used to test for a trend in SMR by time since first registration. Significance was calculated at the 5% level and two-sided significance tests were used in all analyses.

It was not possible to ascertain a date of birth for 52 (4%) of the new study members from the Royal College of Radiologists, the General Medical Council or the NHSCR or by correspondence. An approximate year of birth had to be estimated for each of these radiologists by subtracting 35 years (the new study members' median age at first registration) from their year of first registration. As 44 of these radiologists had emigrated soon after registering they contributed a total of only 204 years of observation to the study. A sensitivity analysis showed that gross differences in the assumptions used to estimate year of birth did not alter the conclusions of any of the analyses.

Results

Mortality from all causes

The results of the follow-up of the 2698 male radiologists included in this study are shown in Table 1. At the end of the previous follow-up (1 January 1977) all the radiologists who registered prior to 1921 had died. By the end of this follow-up only 3 (1%) of those who registered between 1921 and 1935 and 158 (24%) of those who registered between 1936 and 1954 were still alive and living in the UK. There were unusually high numbers of emigrations (31%) in the group who registered between 1955 and 1979. This appeared to be owing to large numbers of radiologists coming to the UK to be trained but leaving soon afterwards.

Among radiologists aged less than 85 years,

Table 1. Vital status of all male radiologists on 1 January 1997

Status on 1 January 1997	*n* by year of first registration				
	1897–1920	1921–1935	1936–1954	1955–1979	Total
Alive and living in UK	0 (0%)	3 (1%)	158 (24%)	802 (59%)	963 (36%)
Dead[a]	321 (95%)	319 (89%)	404 (62%)	114 (8%)	1158 (43%)
Emigrated	18 (5%)	35 (10%)	84 (13%)	413 (31%)	550 (20%)
Lost to follow-up	0 (0%)	0 (0%)	4 (1%)	23 (2%)	27 (1%)
Total	339 (100%)	357 (100%)	650 (100%)	1352 (100%)	2698 (100%)
Person years at risk[b]	9737	11443	21739	26696	69615

[a]This includes deaths >84 years of age—the numbers by year of first registration group were 31 (1897–1920), 48 (1921–1935), 36 (1936–1954) and 1 (1955–1979).
[b]Years of observation >84 years of age have been excluded.

there were 752 deaths in those who first registered with a radiological society after 1920. This was significantly lower than the number expected from mortality rates in the general population (SMR=0.72; 95% CI 0.67–0.77), as shown in Table 2. Compared with mortality rates in social class I males and with male medical practitioners, the number of deaths in those who first registered after 1920 was also significantly reduced. When the radiologists were subdivided by year of first registration (1921–1935, 1936–1954 and 1955–1979) there was a significant deficit of deaths in all three groups compared with the general population. However, compared with social class I males and medical practitioners the reductions were statistically significant only in the group of radiologists who registered most recently (1955–1979).

Cancer mortality

Among radiologists registering after 1920 there were significantly fewer cancer deaths than expected from mortality rates in the general population (SMR=0.63; 95% CI 0.54–0.74) and from mortality rates for social class I males (SMR=0.82; 95% CI 0.70–0.96). Compared with male medical practitioners the number of cancer deaths observed was slightly greater than the number expected (SMR=1.04; 95% CI 0.89–1.21). When the data were subdivided by year of first registration the number of observed deaths from cancer exceeded the number expected for those who first registered during 1921–1935 (SMR=1.24; 95% CI 0.93–1.63) and during 1936–1954 (SMR=1.12; 95% CI 0.89–1.39), although the increase was not statistically significant in either case. For the radiologists who registered after 1954 there were fewer cancer deaths than expected in medical practitioners (SMR=0.71; 95% CI 0.49–1.003). When all four groups were considered (including those who registered before 1921) there was a significantly decreasing trend in the SMRs for all cancers with increasing year of first registration for all the comparison populations (χ_1^2=23.5, 16.1 and 17.8 compared with the general population, social class I males and male medical practitioners respectively, $p<0.001$ in all cases), see Figure 1 (top panel).

Cancer mortality by time since first registration

The previous follow-up of the radiologists found evidence of an increasing trend in the SMRs for cancer deaths with respect to the number of years since first registration with a radiological society. The trend was just statistically significant for the men who first joined a radiological society after 1920. With the extra years of follow-up and the addition of the new group of radiologists a similar trend was still evident and the statistical evidence for this trend had increased (χ^2=9.99, p=0.002 compared with mortality rates for medical practitioners), see Figure 2 (top panel) and Table 3. The numbers of observed cancer deaths were fewer than the numbers expected from rates for medical practitioners during the periods 0–9 (SMR=0.57) and 10–19 (SMR=0.71) years after first registration, slightly more than expected for 20–29 (SMR=1.04) and 30–39 (SMR=1.12) years after first registration and significantly more than expected 40+ years after first registration (SMR=1.41; 95% CI 1.03–1.90).

Radiologists registering during 1921–1935 and 1936–1954 contributed to the increased risk at 40+ years after first registration. Few who registered during 1955–1979 have yet been followed up for 40+ years but there is no evidence to date of any increase in risk in this group.

Mortality from specific cancers

During the period 20 or more years after first registration there was a significant excess of cancer deaths in the post-1920 radiologists compared with medical practitioners (SMR=1.17; 95% CI 1.01–1.34). In order to investigate the nature of this excess, these cancer deaths were analysed

Table 2. Observed (O) and expected (E) deaths in male radiologists by cause and year of first registration (SMR, standardized mortality ratio)

Cause of death		Year of first registration																	
		1897–1920			1921–1935			1936–1954			1955–1979			All post-1920			Total		
		O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR
All causes	(i)	290	304.26	0.95	271	338.58	0.80***	368	483.90	0.76***	113	226.07	0.50***	752	1048.55	0.72***	1042	1352.82	0.77***
	(ii)		280.56	1.03		292.73	0.93		373.53	0.99		162.76	0.69***		829.02	0.91**		1109.58	0.94*
	(iii)		300.50	0.97		295.71	0.92		367.23	1.00		165.69	0.68***		828.63	0.91**		1129.13	0.92**
All cancers[a]	(i)	60	47.16	1.27	51	67.55	0.76	85	128.77	0.66***	32	69.36	0.46***	168	265.68	0.63***	228	312.84	0.73***
	(ii)		41.41	1.45**		55.02	0.93		96.87	0.88		52.57	0.61**		204.46	0.82**		245.87	0.93
	(iii)		34.20	1.75***		41.02	1.24		75.84	1.12		45.03	0.71		161.89	1.04		196.09	1.16*
All non-cancers	(i)	230	257.10	0.89	219	271.03	0.81***	278	355.13	0.78***	77	156.71	0.49***	574	782.87	0.73***	804	1039.98	0.77***
	(ii)		239.15	0.96		237.71	0.92		276.66	1.00		110.19	0.70**		624.56	0.92*		863.71	0.93*
	(iii)		266.30	0.86*		254.69	0.86*		291.39	0.95		120.66	0.64***		666.74	0.86***		933.04	0.86***

Expected deaths calculated using rates for (i) all men in England and Wales, (ii) all social class I males and (iii) all male medical practitioners.
All deaths and years of observation >84 years of age have been excluded.
[a]ICD-9 codes 140–239.
The 10 deaths of unknown cause have been censored on the date of death in the analyses of all cancer and all non-cancer deaths.
The results for the group 1897–1920 differ slightly from those reported by Smith and Doll as we have excluded deaths and years of observation >84 years.
*$p<0.05$; **$p<0.01$; ***$p<0.001$.

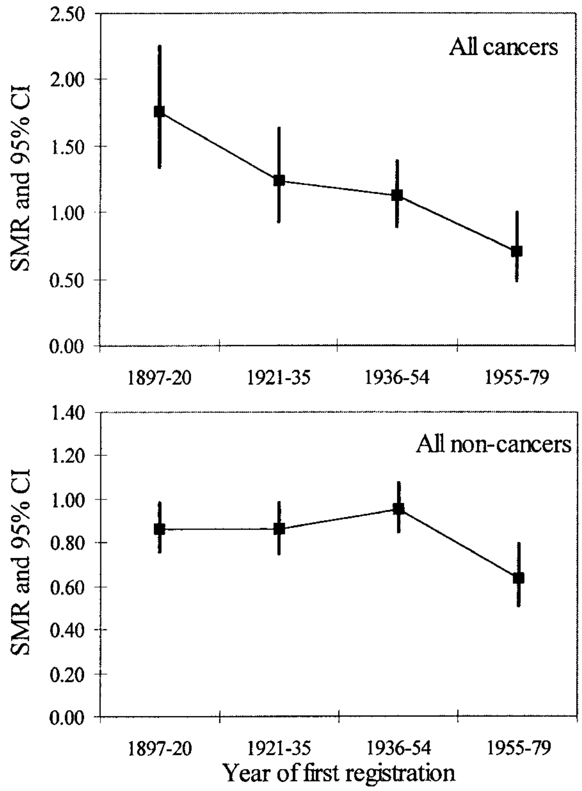

Figure 1. Standardized mortality ratios (SMRs) and 95% confidence intervals (CIs) for all cancer and all non-cancer deaths for all male radiologists compared with medical practitioners by year of first registration.

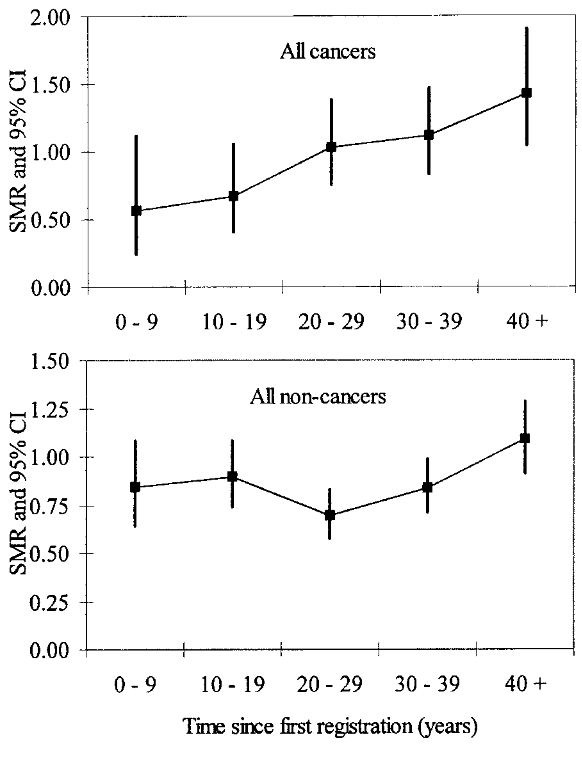

Figure 2. Standardized mortality ratios (SMRs) and 95% confidence intervals (CIs) for all cancer and all non-cancer deaths in post-1920 male radiologists compared with medical practitioners by number of years since first registration.

according to cancer site. Table 4 presents the cancer deaths that occurred more than 20 years after first registration for the cancer sites that were previously investigated by Smith and Doll plus multiple myeloma and non-Hodgkin's lymphoma. Death rates for specific cancers were available for social class I males using the method described earlier, but for medical practitioners SMRs have not been published for specific cancer sites. Approximate adjusted SMRs for medical practitioners were calculated, therefore, by multiplying the SMR for social class I by 1.28, the ratio of the expected number of all cancer deaths in social class I males >20 years after first registration (153.63) to that in medical practitioners (119.72).

In all post-1920 radiologists there were no significantly raised SMRs in any of the cancer sites that had been examined by Smith and Doll compared with expected numbers in social class I males (see Table 4). The greatest proportional excess in the post-1920 radiologists was in leukaemia and the number of deaths was greater than the number expected for all three post-1920 groups defined by the year of first registration. In total, in the post-1920 radiologists, there were eight deaths from leukaemia 20 or more years after first registration and 4.26 expected in social class I males (SMR=1.88; 95% CI 0.81–3.70). For prostate, skin and stomach cancer the SMRs also were greater than 1 (SMR=1.26, 1.09 and 1.03 respectively). In the SMRs adjusted to give an approximate comparison with medical practitioners the SMRs were significantly raised for leukaemia (SMR=2.40; 95% CI 1.04–4.73) and for prostate cancer (SMR=1.61; 95% CI 1.00–2.44). In addition to the eight deaths 20 or more years after first registration in the post-1920 radiologists, one further leukaemia death occurred 9 years after first registration (compared with 1.85 expected <20 years after first registration).

Among the cancer sites not specifically reported in Smith and Doll's analysis the greatest number of deaths was from non-Hodgkin's lymphoma; there were significantly more deaths than expected in social class I males; nine compared with 3.74 expected (SMR=2.41; 95% CI 1.10–4.57). There was also a non-significant excess of multiple myeloma deaths, four compared with 2.32 expected in social class I males. All four multiple myeloma deaths were in the cohort who registered between 1936 and 1954.

Mortality from other causes

The total number of non-cancer deaths at ages less than 85 (among radiologists first registering in the entire period 1897–1979) was significantly

Table 3. Observed (O) and expected (E) numbers of cancer deaths in all male radiologists by number of years since first registration (SMR, standardized mortality ratio)

Years since first registration	Year of first registration															
	1897–1920			1921–1935			1936–1954			1955–1979			All post-1920			
	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	(95% CI)
0	6	4.05	1.48	1	3.22	0.31	5	4.51	1.11	2	6.37	0.31*	8	14.10	0.57	(0.24, 1.12)
10	8	7.18	1.11	6	6.63	0.90	7	9.21	0.76	7	12.20	0.57	20	28.04	0.71	(0.44, 1.10)
20	18	9.59	1.88*	13	10.25	1.27	17	16.20	1.05	14	15.87	0.88	44	42.32	1.04	(0.76, 1.40)
30	19	8.13	2.34**	20	10.95	1.83*	23	24.89	0.92	9	10.42	0.86	52	46.26	1.12	(0.84, 1.47)
40+	9	5.25	1.71	11	9.96	1.10	33	21.02	1.57*	0	0.16	0.00	44[a]	31.14	1.41	(1.03, 1.90)*
χ^2 (trend)		1.35			1.81			2.58			2.08			9.99		
p		0.25			0.18			0.11			0.15			0.002		

Expected deaths calculated using medical practitioners death rates.
All deaths and years of observation >84 years of age have been excluded.
[a]41 cancers (pharynx, oesophageal (2), stomach (4), intestinal (2), colorectal (2), pancreas, lung (9), prostate (9), bladder, kidney, non-Hodgkin's lyphoma (2), multiple myeloma (2), lymphocytic leukaemia (2) and malignant, site unspecified (3)) plus cerebral tumour, polycythaemia and carcinoid disease of the ileum.
$^{*}p<0.05$; $^{**}p<0.01$.

lower than expected from the general population (SMR=0.77; 95% CI 0.72–0.83), from social class I males (SMR=0.93; 95% CI 0.87–0.99) and from medical practitioners (SMR=0.86; 95% CI 0.80–0.92), see Table 2. When the cohort was subdivided by year of first registration the observed number of non-cancer deaths was lower than the number expected from medical practitioners in all four groups, and significantly lower among those registering in 1897–1920, 1921–1935 and 1955–1979. Among those first registering before 1921, and who are likely to have received the highest radiation exposures, the number of deaths from circulatory disease was significantly lower than expected for medical practitioners, while for respiratory diseases and all other non-cancer diseases the observed numbers did not differ significantly from those expected (see Table 5). There was no evidence of a trend in the SMRs for non-cancer deaths by year of first registration compared with medical practitioners (χ_1^2=1.2; p=0.27), see Figure 1 (bottom panel). Neither was there evidence of a trend in SMR by time since first registration in the post-1920 radiologists (p=0.10), see Figure 2 (bottom panel) or in the pre-1921 radiologists (p=0.19), see Table 6.

Discussion

We have expanded the cohort of British radiologists to include those who first registered with the Royal College of Radiologists between 1955 and 1979, and have followed the cohort for a further 20 years until 1 January 1997. The main aim of this study was to assess whether there was evidence of an increased risk of cancer mortality in radiologists who first registered with a radiological society after 1921. We also examined whether radiologists were at increased risk of death from diseases other than cancer.

Among the radiologists entering the profession after 1920, there were significantly fewer deaths from all causes than expected in the general population both overall and among those who first registered in each of the three calendar periods 1921–1935, 1936–1954 and 1955–1979 (Table 2). Compared with medical practitioners and social class I males this result was also true overall, but when the three entry cohorts were examined separately there was a significant deficit only in the most recent group of radiologists, that is those entering the profession between 1955 and 1979. The low mortality in this group compared with medical practitioners was due to low numbers of deaths from both cancer (32 deaths compared with 45.03 expected) and other causes (77 compared with 120.6 expected). The low death rate in this group is likely to be at least partly

Table 4. Observed (O) and expected (E) deaths from specific cancers in male radiologists that occurred >20 years after first registration (SMR, standardized mortality ratio)

Cancer site (ICD-9 code)	Year of first registration															
	1897–1920			1921–1935			1936–1954			1955–1979			All post-1920			
	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	SMR^{adj}
Sites included in Smith and Doll's analysis																
Oesophagus (150)	2	1.60	1.25	1	1.42	0.70	1	2.85	0.35	0	1.50	0.00	2	5.77	0.35	0.44
Stomach (151)	5	3.63	1.38	5	3.88	1.29	5	5.18	0.97	1	1.67	0.60	11	10.73	1.03	1.31
Intestine (152–3)	6	4.72	1.27	4	4.75	0.84	4	7.81	0.51	2	3.20	0.63	10	15.76	0.63	0.81
Rectum (154)	1	2.97	0.34	2	2.72	0.74	2	4.09	0.49	3	1.63	1.84	7	8.44	0.83	1.06
Pancreas (157)	5	1.29	3.88*	2	2.29	0.87	4	4.12	0.97	1	1.62	0.62	7	8.03	0.87	1.12
Lung (162–3)	7	2.84	2.46	11	10.37	1.06	14	19.00	0.74	0	6.47	0.00	25	35.84	0.70	0.89
Prostate (185)	7	3.27	2.14	2	4.57	0.44	15	9.56	1.57	5	3.33	1.50	22	17.46	1.26	1.61*
Bladder (188)	3	1.20	2.50	1	2.11	0.47	3	3.81	0.79	1	1.27	0.79	5	7.19	0.70	0.89
Skin (173)	2	0.46	4.35	2	0.44	4.55	0	0.91	0.00	0	0.49	0.00	2	1.84	1.09	1.39
Leukaemia (204–7)	1	0.40	2.50	3	1.11	2.70	4	2.29	1.75	1	0.86	1.16	8	4.26	1.88	2.40*
Additional sites of interest and other sites																
Non-Hodgkin's lymphoma (200, 202)	0	0.08	0.00	0	0.60	0.00	6	2.05	2.93*	3	1.09	2.75	9	3.74	2.41*	3.08**
Multiple myeloma (203)	0	0.00	0.00	0	0.17	0.00	4	1.43	2.80	0	0.72	0.00	4	2.32	1.72	2.21
Other sites	7	6.58	1.06	11	7.71	1.43	11	16.85	0.65	6	7.69	0.78	28[a]	32.35	0.86	1.10
All cancers	46	29.04	1.58**	44	42.14	1.04	73	79.95	0.91	23	31.54	0.73	140	153.63	0.91	1.17*

Expected deaths based upon rates in social class I males.
All deaths and years of observation >84 years of age have been excluded.
[adj]Approximate SMRs compared with medical practitioners (except SMR=1.17 for all cancers which is the actual value). See text for method of calculation.
[a]25 cancers (pharynx (2), gallbladder (2), larynx, myosarcoma, astrocytoma (3), breast, liver (3), kidney (6), thyroid and unspecified malignant (5)) plus cerebral tumour, polycythaemia and carcinoid disease of the ileum.
*$p<0.05$; **$p<0.01$.

Table 5. Observed (O) and expected (E) deaths from causes other than cancer in male radiologists by year of first registration (SMR, standardized mortality ratio)

Cause of death		Year of first registration															
		1897–1920			1921–1935			1936–1954			1955–1979			Total			
		O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	(95% CI)
Circulatory[a]	(i)	127	123.52	1.03	151	157.67	0.96	192	233.13	0.82**	44	106.11	0.41***	514	620.43	0.83	(0.76, 0.90)***
	(ii)		134.65	0.94		156.75	0.96		185.56	1.03		73.58	0.60***		550.54	0.93	(0.85, 1.02)
	(iii)		160.52	0.79**		182.76	0.83*		196.59	0.98		74.98	0.59***		614.85	0.84	(0.77, 0.91)**
Respiratory[b]	(i)	35	45.93	0.76*	23	54.64	0.42***	27	63.17	0.43***	8	18.66	0.43**	93	182.40	0.51	(0.41, 0.62)***
	(ii)		26.92	1.30		23.99	0.96		24.37	1.11		7.23	1.11		82.51	1.13	(0.91, 1.38)
	(iii)		37.38	0.94		25.81	0.89		20.09	1.34		5.95	1.34		89.23	1.04	(0.84, 1.28)
All other diseases (non-cancer)	(i)	61	75.03	0.81	32	47.24	0.68*	35	45.09	0.78	14	19.76	0.71	142	187.12	0.76	(0.64, 0.89)***
	(ii)		66.56	0.92		46.54	0.69*		54.74	0.64**		20.44	0.68		188.28	0.75	(0.64, 0.89)***
	(iii)		50.49	1.21		26.45	1.21		50.80	0.69*		24.54	0.68		152.28	0.93	(0.79, 1.10)
External causes[c]	(i)	7	12.62	0.55	13	11.48	1.13	24	13.74	1.75*	11	12.18	0.90	55	50.02	1.10	(0.83, 1.43)
	(ii)		11.02	0.64		10.43	1.25		11.99	2.00**		8.93	1.23		42.37	1.30	(0.98, 1.69)
	(iii)		17.91	0.39*		19.68	0.66		23.91	1.00		15.19	0.72		76.69	0.72	(0.54, 0.93)**

Expected deaths calculated using rates for (i) all men in England and Wales, (ii) all social class I males, and (iii) all male medical practitioners.
All deaths and years of observation >84 years of age have been excluded.
[a]ICD-9 codes 390–459; [b]ICD-9 codes 460–519; [c]ICD-9 codes E800–E999.
*$p<0.05$; **$p<0.01$; ***$p<0.001$.

Table 6. Observed (O) and expected (E) numbers of non-cancer deaths in male radiologists by number of years since first registration (SMR, standardized mortality ratio)

Years since first registration	Year of first registration															
	1897–1920			1921–1935			1936–1954			1955–1979			All post-1920			
	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	O	E	SMR	(95% CI)
0	22	34.46	0.64	22	29.03	0.76	25	23.16	1.08	14	20.23	0.69	61	72.42	0.84	(0.64, 1.08)
10	47	52.33	0.90	37	44.62	0.83	46	41.55	1.11	25	33.94	0.74	108	120.11	0.90	(0.74, 1.09)
20	60	68.57	0.88	42	57.52	0.73*	52	68.90	0.75*	21	39.59	0.53**	115	166.01	0.69	(0.57, 0.83)***
30	56	66.10	0.85	57	65.37	0.87	76	87.50	0.87	17	26.44	0.64	150	179.31	0.84	(0.71, 0.98)*
40+	45	44.82	1.00	61	58.17	1.05	79	70.29	1.12	0	0.46	0.00	140	128.92	1.09	(0.91, 1.28)
χ^2 (trend)		1.71			2.42			0.04			0.36			2.78		
p		0.19			0.12			0.84			0.55			0.10		

Expected deaths calculated using medical practitioners death rates.
All deaths and years of observation >84 years of age have been excluded.
$^*p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

owing to the healthy worker effect not yet having completely worn off, as the group has not been followed up for as long as the other cohorts.

Although there were fewer deaths from all causes in the post-1920 radiologists than expected from death rates for medical practitioners, the number of deaths from cancer was close to the number expected (Table 2). In this group there was a progressive increase in the SMRs for cancer with number of years since first registration, culminating in a significantly raised SMR of 1.41 (95% CI 1.03–1.90) in the period more than 40 years after first registration (Table 3). As no such trend was apparent for deaths from all other causes (Table 6) it suggests that the finding in the cancer deaths is not an artefact of study methodology. The raised risk is entirely accounted for by radiologists who first registered during the periods 1921–1935 and 1936–1954, who are likely to have had higher doses of radiation than those who entered later. Within these groups the highest SMRs occur 30–39 and 40+ years since first registration, by which time many individuals would have accumulated their final total dose.

The interpretation of risk associated with specific cancers was limited because of the relatively small number of deaths at each site and also because precise comparison rates were not available for medical practitioners, which are probably a more appropriate comparison for radiologists than all social class I males. The largest excess risks were for leukaemia (SMR=1.88) and for prostate cancer (SMR=1.26) (Table 4). Significantly increased risks of leukaemia have been found in other studies of radiologists in the United States (SMR=2.59 in radiologists registered between 1920 and 1929 compared with general physicians) [15] and in China (SMR=2.4; 95% CI 1.3–4.1)) where the year of first employment was from 1926 to 1985 [16]. The US study also found a small excess risk of prostate cancer (SMR=1.33, not significantly increased) but prostate cancer was not reported in the Chinese study as it is uncommon in China. Acute high doses of radiation are known to cause leukaemia, as seen among the atomic bomb survivors [17] and the patients treated with X-rays for ankylosing spondylitis [18]. Results for prostate cancer from these studies are less clear; there is no evidence of an excess risk in the Japanese atomic bomb survivors (who normally have a very low risk of the disease) but a small, significant excess was seen in the ankylosing spondylitis patients.

Among the sites of cancer not previously reported by Smith and Doll there was a significant excess of non-Hodgkin's lymphoma and a non-significant excess of deaths from multiple myeloma. In the most recent analysis of the Japanese atomic bomb survivors there was some evidence of an increased risk of lymphoma (Hodgkin's and non-Hodgkin's) in males but not in females and, contrary to previous analyses, there was no evidence of an excess risk for multiple myeloma [17]. The studies of the early US radiologists and the ankylosing spondylitis patients have reported significant excesses of non-Hodgkin's lymphoma also [15,18], but no increased risk was found in the Chinese radiologists [16].

Because of the clear dose–response relationships that have recently been reported for non-cancer causes of death in the survivors of the atomic bombings at Hiroshima and Nagasaki [3], the non-cancer causes of death were investigated in detail in these radiologists for the first time. Mortality from most of the non-cancer causes of death was lower than in the comparison populations and there were no significantly increasing or decreasing trends in the risks across the cohorts or by number of years since first registration (Tables 5 and 6). There was no evidence of significant excess risks in mortality from circulatory or respiratory diseases, even in the pre-1921 radiologists who would have received the highest radiation exposures. The small excess risk of death from respiratory diseases in the two most recent cohorts of radiologists may be a chance finding. It was also reported for radiologists in a study of causes of mortality in NHS consultants, which would have included some individuals in the present study [19].

The recently reported increase in the excess risk of non-cancer deaths from radiation exposure in the atomic bomb survivors is unlikely to be a chance finding, but the biological mechanism is still unclear. Two other major studies have recently reported a relationship between radiation exposure and non-cancer causes of death. An overview of randomized trials of radiotherapy for breast cancer [20] found a statistically significant increase in the annual death rate from causes other than breast cancer in those treated with radiotherapy, many of whom in consequence have received a large dose to the heart and large vessels. The increase was not apparent until more than 10 years after radiotherapy and appeared mainly to involve vascular deaths. The combined analysis of nuclear industry workers from several countries, who will have received relatively small doses measured in mGy, also reported a significantly increasing trend in circulatory diseases with increasing radiation dose [21].

All studies of radiologists have been limited by their lack of individual dose information. This prevents estimation of dose–response relationships and comparisons of risk estimates with those obtained from other studies of radiation exposure. However, several reports have attempted to estimate annual exposures to radiologists. Braestrup in 1958 [22] estimated that radiologists in the 1920s and 1930s could have been exposed to 100 roentgens per year (roughly equivalent to 1 Sv or 1 Gy per year). Smith and Doll estimated that annual exposure was 0.1 Sv per year before the 1950s and perhaps 0.05 Sv in the early fifties. Reports by the National Radiological Protection Board (NRPB) estimated a mean annual dose of less than 5 mSv by 1964 [23] and that this has further declined to an average of 0.5 mSv by 1993 [24]. We have used these estimates of radiation exposure to assess the consistency of our risk estimates with those of the Life Span Study (LSS), the study of the atomic bomb survivors [3,25]. These rough comparisons were made under the assumption that the average age of registration with a radiological society in this study was 35 years, and by taking a conservative estimate that radiologists would be exposed for an average of 20 years (Table 7).

The cancer risks observed were lower than those predicted by the LSS data for all four groups of radiologists. The observed risks for cancer in the radiologists registering before 1955, although greater than one, were between two and seven times smaller than the predictions from the LSS. There could be several explanations for this, including the healthy worker effect as mentioned above. In addition there is some evidence that fractionation of radiation exposure reduces the risk of cancers other than leukaemia by at least one half [26]. If this factor were applied the risks observed in the radiologists, though still lower, would be more consistent with those from the LSS. The predicted SMR for 1897–1920 would be 4.8, 1.7 for 1921–1935, 1.2 for 1936–1954 and 1.02 for 1955–1979. However, the differences could also be a result of the dose approximation and could suggest that the average lifetime radiation exposure was actually considerably lower in these radiologists than estimated—particularly in the earliest group of radiologists (1897–1920). Related to this is the fact that the highest dose category considered in the LSS in the estimation of the excess relative risk per Sievert was $\geqslant 2$ Sv. Therefore to estimate the risks for the first and second cohort the LSS models had to be extrapolated to estimate effects at much higher dose levels (20 Sv and 3.8 Sv for those first registering in 1897–1920 and 1921–1935 respectively).

All observed SMRs for circulatory diseases and non-cancer diseases as a whole were lower than one, and therefore inconsistent with the predictions based on the risks in the LSS. Even taking into account the limitations of the methods outlined above, the predictions indicate that a clear excess would have been expected in the early groups of radiologists who received the highest doses and in whom there was a highly significant

Table 7. Comparison of the observed radiation risks in the radiologists with the predicted risks for radiologists based upon estimates from the atomic bomb survivors (SMR, standardized mortality ratio)

Cause of death	1897–1920				1921–1935				1936–1954				1955–1979			
	Observed		Predicted		Observed		Predicted		Observed		Predicted		Observed		Predicted	
	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)	SMR	(90% CI)
Cancer	1.75	(1.40–2.17)	6.2	(3.6–8.6)	1.24	(0.97–1.57)	2.0	(1.5–2.4)	1.12	(0.93–1.34)	1.3	(1.2–1.5)	0.71	(0.52–0.95)	1.03	(1.01–1.04)
Non-cancer diseases[a]	0.90	(0.80–1.00)	3.4	(2.8–4.0)	0.88	(0.78–0.98)	1.5	(1.3–1.6)	0.95	(0.85–1.05)	1.15	(1.1–1.2)	0.63	(0.51–0.77)	1.01	(1.01–1.02)
Circulatory diseases	0.79	(0.68–0.92)	2.8	(1.4–4.4)	0.83	(0.72–0.95)	1.3	(1.1–1.7)	0.98	(0.86–1.10)	1.1	(1.03–1.2)	0.59	(0.45–0.75)	1.01	(1.0–1.02)
Respiratory diseases	0.94	(0.69–1.24)	4.6	(2.2–7.2)	0.89	(0.61–1.26)	1.7	(1.2–2.2)	1.34	(0.95–1.85)	1.2	(1.08–1.4)	1.34	(0.67–2.42)	1.02	(1.01–1.03)

Observed SMRs and 90% CIs are from Tables 2 and 5 and are based on the expected rates for all medical practitioners.
The predicted SMR was calculated as the (excess relative risk per Sv × estimated average lifetime dose)+1.
The excess relative risk per Sv and 90% CI for the atomic bomb survivors is 0.26 (0.13–0.38) for solid cancers in males aged 40 years at exposure, 0.12 (0.09–0.15) for non-cancer diseases, 0.09 (0.02–0.17) for circulatory disease and 0.18 (0.06–0.31) for respiratory diseases [3, 27].
The average lifetime dose for each group (according to year of first registration) was estimated to be 20 Sv in those who registered between 1897 and 1920, 3.8 Sv for 1921–1935 radiologists, 1.25 Sv in 1936–1954 radiologists and 0.1 Sv in radiologists registering between 1955 and 1979.
[a]Excluding external causes of death.

75% increase in cancer mortality compared with all medical practitioners. Among the atomic bomb survivors a dose sufficient to cause a 75% increase in cancer mortality caused a 35% increase in mortality from non-cancer diseases, whereas in the present study the pre-1921 radiologist mortality rates from non-cancer diseases were 10% lower than rates in all medical practitioners (95% CI −20% to 0%). The explanation for the different findings for diseases other than cancer in the 1897–1920 and 1921–1935 radiologists and the atomic bomb survivors is as yet unclear.

In conclusion, the excess risk of cancer mortality in the period more than 40 years after first registration is probably a long-term effect of radiation exposure in those who first registered during 1921–1935 and 1936–1954. There was no evidence of an increase in cancer mortality among radiologists who first registered after 1954, in whom radiation exposures are likely to have been lower. For non-cancer causes of death there was no evidence of an increased risk in any group, even among those registering before 1921.

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