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Occupational radiation exposure and cancer incidence in a cohort of diagnostic medical radiation workers in South Korea

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ABSTRACT

Objectives We investigated the association between protracted low-dose ionising radiation and the risk of cancer in medical radiation workers, the largest group of workers with occupational radiation exposures.
Methods Data of all South Korean diagnostic medical radiation workers enrolled at the National Dose Registry during 1996–2011 were merged with the death and cancer incidence data until 31 December 2017. SIRs, relative risks and excess relative risks (ERRs) for cancer were calculated to quantify the radiation dose–response relationship using Poisson regression models.
Results A total of 3392 first primary cancer cases were identified among 93 920 diagnostic medical radiation workers. The mean cumulative badge dose in the cohort was 7.20 mSv. The ERRs for solid cancer with a 5-year lag and haematopoietic cancers with a 2-year lag for all workers were 0.15 per 100 mGy (95% CI −0.20 to 0.51) and 0.09 per 100 mGy (95% CI −2.02 to 2.20), respectively. The ERRs for cancers did not significantly vary by job title, different lag years or after excluding thyroid and lung cancers. Sensitivity analyses restricted to workers employed for at least 1 year, or who were employed in or after 1996, or who had exposure to a cumulative badge dose of 1 mSv or more showed similar results.
Conclusions Occupational radiation doses were not significantly associated with cancer incidence among South Korean diagnostic medical radiation workers. However, cautious interpretation of ERRs is needed due to the limitations of short follow-up and low cumulative radiation doses.

Key messages

What is already known about this subject?
- ► A few studies have reported findings on health effects associated with protracted low-dose radiation exposures among medical radiation workers.
- ► However, the increased risks were mainly limited in the early period of workers who had prolonged exposure at high doses of radiation.
- ► There has been a rapid increase in the number of medical radiation workers with changes in their working environments, such as increasing implementation of new imaging techniques and radiation protection measures.

What are the new findings?
- ► Diagnostic medical radiation workers in South Korea showed differences in cancer incidence compared with the general population depending on sex and cancer site.
- ► Positive but not significant excess relative risks for cancer were observed, with similar results in study populations according to demographic and occupational characteristics.

How might this impact on policy or clinical practice in the foreseeable future?
- ► The findings contribute to a better knowledge of the health effects of low-dose chronic radiation exposures from a recently constructed cohort of medical radiation workers.
- ► More efforts to implement radiation protective measures should continue to minimise the potential health risks among medical radiation workers.

INTRODUCTION

Occupational radiation exposure studies provide an opportunity to directly investigate the health effects of external sources of ionising radiation.[1] Medical radiation workers were among the first to be investigated for radiation-induced cancer risks and epidemiological studies of medical radiation workers have reported an increased risk of a few cancer sites.[2] Medical radiation workers comprise more than half of all radiation workers exposed to man-made sources of radiation and a rapidly increasing professional group due to the expanding use of modern medical practices worldwide.[3] These workers receive a protracted low level of radiation exposure, in which the nature of the exposure is qualitatively similar to that received by the general population, and are an identifiable professionally certified population, many of whom are women, with routinely obtained information on radiation exposure.

A few studies on medical radiation workers have reported important findings for direct observational evidence on health effects associated with chronic low-dose radiation exposures.[2 4 5] However, the increased risks were mainly observed in the early period of exposure for prolonged exposures at doses higher than those currently reported and the studies do not include occupational exposure from

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new diagnostic imaging techniques.[5] The average annual doses received by medical radiation workers have decreased dramatically, owing to technological advances in X-ray equipment and radiation protection measures to protect both patients and workers from the health effects of ionising radiation. Additionally, most studies ended the follow-up before the 2000s and have limited information on individual radiation organ doses and lifestyle factors.

In South Korea, medical radiation workers account for the majority of radiation workers (http://www.cdc.go.kr). We constructed a registry-based cohort by combining information on diagnostic medical radiation workers enrolled in the National Dose Registry (NDR) with national cancer incidence and mortality data in South Korea. Historical radiation dose reconstruction was performed and organ-specific radiation doses were estimated for the cohort.[6] The findings of overall mortality,[7] thyroid cancer incidence,[8] circulatory disease morbidity,[9] suicide death[10] and projected lifetime cancer risks[11] were reported for this cohort. We have extended this study by linking the latest data on cancer incidence to investigate the role of occupational radiation exposure in cancer development among diagnostic medical radiation workers.

METHODS

Study population

The study population and methods have been described previously.[7 8] Briefly, the study population comprised all diagnostic medical radiation workers enrolled in the NDR between 1 January 1996 and 31 December 2011 (n=94 394). The cohort included radiological technologists, radiologists, physicians (non-radiologists), dentists, dental hygienists, nurses and others including medical assistants. Among workers whose data were registered in the database, those with any cancer before enrolment (n=462) or those who had invalid NDR information (n=12) were excluded. The analysis was therefore conducted on 93 920 workers.

Ascertainment of cancer incidence and vital status

Cancer incidence was ascertained by linkage to the Korean Central Cancer Registry (KCCR), a centralised national registry of the Korean National Cancer Center, on request. Personal identification numbers were used for establishing a deterministic linkage. The KCCR provides the most completed and comprehensive data (98.2%)[12] regarding cancer codes, site, histological types, stage and date of diagnosis for all cancers identified in cohort members. Vital status was ascertained by Statistics Korea using a linkage method similar to the one used for the KCCR linkage. We followed up all diagnostic medical radiation workers for cancer incidence linkage with national cancer registry and national vital statistics until 31 December 2017.

Definition of cancer outcomes

We defined cancer cases as the first primary malignant tumours determined by the International Classification of Diseases and Related Health Problems, 10th Revision (ICD-10) code (C00-C99).[13] We selected cancer sites or groups based on a priori interests. First, we included individual organ sites for which there was sufficient evidence or positive association for the carcinogenicity of X-rays and gamma-radiation; medical radiation workers are often exposed to these types of ionising radiation, as revealed by an International Agency for Research on Cancer monograph.[14] We limited the analysis to cancer sites with 30 or more cases. Since only two cases of chronic lymphocytic leukaemia (CLL) were observed in this cohort and an association has been reported between CLL and radiation exposure,[15] we included CLL as a leukaemia category. Second, we considered a few groups of cancers, that is, all cancer combined, solid cancers and haematopoietic cancers defined by ICD-10 codes C00-C99, C00-C81 and C81-C96, respectively. We included non-melanoma skin cancer in the definition of all cancers because the KCCR has provided reliable nationwide incidence data of histologically confirmed non-melanoma skin cancers since 1999.[16] Third, we considered solid cancers other than thyroid cancer cases owing to its high proportion of total cancers and potential overdiagnosis in South Korea.[17] We additionally excluded lung cancer to indirectly minimise the potential effect of smoking because no individual data on lifestyle factors were available in this registry-linked cohort.

Estimation of occupational characteristics and radiation dose

Occupational exposure data were obtained from the NDR database. The Korean Disease Control and Prevention Agency maintains the NDR system for all diagnostic medical radiation workers since 1996. Badge dose measurements, using a personal thermoluminescent dosimeter, were performed every quarter by five personnel monitoring centres. The standard practice in South Korea involved wearing the dosimeter under aprons on the left side at the level of the chest. The NDR database includes data on workers' name, sex, date of birth, personal identification number, workplace address, occupation, quarterly reported dose data, and the start date and the end date of the measurement period. Using the NDR information, the workers were categorised into seven groups according to job categories. Duration of employment was defined as the period between the beginning and the end of badge measurement for workers enrolled after 1996. For workers enrolled before or in 1996 (14.0% of the total enrollees in the NDR), the start year of radiological practice for each sex and occupational group was imputed to be the mode of the age of job start from previous survey for diagnostic medical radiation workers.[18]

Radiation doses were estimated according to a previous method.[6] Briefly, the annual and cumulative individual badge doses based on H_p[10] were calculated by combining the quarterly badge readings of workers enrolled in the NDR. This effective dose (measured in Sievert) has the lowest detectable level of 0.01 mSv per quarterly in the NDR. Historical badge doses were reconstructed for workers who began working with radiation before 1996 using an annual dose model that describes doses as a log-linear function of calendar year and age at the year of exposure. Colon and bone marrow absorbed doses (measured in Gray) were estimated by converting the individual badge dose to each organ-specific dose and multiplying these doses by two conversion coefficients provided by the International Commission on Radiological Protection.[19 20] An anteroposterior irradiation geometry, which is most common in occupational exposure scenarios among medical radiation workers, was assumed. The dominant energy of the diagnostic radiation fields was assumed to be between 30 keV and 40 keV.[21 22] The equation was $H_p\left(d\right)\left[\frac{D_T}{K_a}/\frac{H_p(d)}{K_a}\right]$, where $H_p\left(d\right)$ is the equivalent dose; $\frac{D_T}{K_a}$ is the air kerma-to-organ dose conversion coefficient and $\frac{H_p(d)}{K_a}$ is the air kerma-to-personal dose equivalent conversion coefficient. The organ absorbed doses were adjusted for the probability of apron use and badge placement, which were obtained from a nationwide survey for diagnostic medical

Table 1 Occupational characteristics by sex in South Korean diagnostic medical radiation workers

	Male		Female	
Characteristics	**Number**	**%**	**Number**	**%**
Total	53 582	100.0	40 338	100.0
Occupation				
Radiological technologist	17 222	32.1	9021	22.4
Radiologist	1190	2.2	541	1.3
Dentist	12 178	22.7	3381	8.4
Dental hygienist	75	0.1	13 404	33.2
Nurse	422	0.8	7103	17.6
Other physician	15 780	29.4	2611	6.4
Others	6715	12.5	4277	10.6
Type of facility				
General hospital	11 254	21.0	9871	24.5
Hospital and clinic	26 390	42.3	10 197	25.3
Dental hospital and clinic	12 415	23.2	19 356	47.9
Others	3523	6.6	914	2.3
Area of facility				
Metropolitan	26 534	49.5	23 533	58.3
City	22 550	42.1	15 436	38.3
Rural	4498	8.4	1369	3.4
Calendar year of birth				
<1960	9623	18.0	865	2.1
1960–1969	18 768	35.0	5576	13.8
1970–1979	17 039	31.8	15 856	39.3
≥1980	8152	15.2	18 041	44.7
Age at entry (years)				
<25	10 904	20.3	19 483	48.3
25–30	14 726	27.5	11 231	27.8
30–35	9090	17.0	4833	12.0
35–40	8678	16.2	2800	6.9
≥40	10 184	19.0	1991	4.9
Calendar year of work began				
<1996	9817	18.3	3327	8.3
1996–2004	21 718	40.5	13 405	33.2
≥2005	22 047	41.2	23 606	58.5
Duration of employment (years)				
<1	7427	13.9	10 708	26.5
1–5	15 692	29.3	17 333	43.0
5–10	14 012	26.2	8092	20.1
≥10	16 451	30.7	4205	10.4
Cumulative badge dose (mSv)				
<1	22 021	41.1	26 037	64.5
1–5	12 386	23.1	8877	22.0
5–20	10 504	19.6	4461	11.1
≥20	8671	16.2	963	2.4

radiation workers.[18] The equation for the estimation of organ doses was $D_o = D_c \times R_{coef} \times (P_{NoA} + AA \times P_{AO} + P_{AU})$, where D_o is the organ dose, D_c is the personal cumulative badge dose, R_{coef} is the conversion coefficient, P_{NoA} is the probability of not wearing apron at work, P_{AO} is the probability of wearing the badge outside the apron, P_{AU} is the probability of wearing the badge inside the apron, and AA is the apron attenuation factor. We assumed an attenuation rate of 0.8 for the use of lead aprons to reflect the shielding effect, based on previous studies.[11 21]

Statistical analyses

Each person contributed person-years at risk from 1996 or from the year of the start of work based on the NDR, whichever occurred later. The end of follow-up was taken as the earliest of the following: date of any malignant cancer diagnosis, date of death or 31 December 2017. The DATAB module in Epicure software was used to create a person-year table stratified by sex, attained age (<25, 5-year intervals from the age of 25–84, ≥85 years), calendar year (1996–2000, 2001–2005, 2006–2010, 2011–2017), birth year (<1960, 1960–1969, 1970–1979, ≥1980), year of job entry (<2000, 2000–2004, ≥2005), job titles (seven categories, as described above), year first worked (<1996, 1996–2004, ≥2005), age at first job (<25, 25–30, 30–35, 35–40, ≥40), years of employment duration (<1, 1–5, 5–10, ≥10), type of medical facility (general hospital, hospital and clinic, dental hospital and clinic, others), area of medical facility (metropolitan, city, rural) and cumulative badge dose (<1, 1–5, 5–20, ≥20 mSv).

Crude cancer rates per 100 000 by cancer groups and individual organ sites were calculated by dividing the number of cancers by the person-years in the corresponding groups. SIRs and the corresponding 95% CIs for all cancers and site-specific cancers were calculated using the South Korean cancer incidence rates using Poisson-regression methods. The expected number of incident cancers for each cell was computed as the product of the number of person-years and the sex-specific, age-specific and calendar-year-specific South Korean cancer incidence rates (http://www.ncc.re.kr/). Reference rates were limited to the follow-up period 1999–2017 because nationwide cancer incidence rates were available only from 1999 in South Korea. For the period 1996–1998, we assumed that the cancer incidence rates were the same as those in 1999. Relative risks (RRs) and corresponding 95% CIs were calculated by Poisson regression using the maximum likelihood method. The linear trends of RRs with cumulative badge dose categories was examined by using simple dose–response models.

Excess relative risks (ERRs) and 95% CIs for cancer incidence were calculated using Poisson regression to analyse the relationship between cumulative organ doses and cancer incidence. The primary model used to evaluate the dose–response assumes a linear dose–response relationship as classically used in radiation epidemiology.[23] The linear model can be written as $RR=1+\beta d$, where RR is the relative risk, d is the dose and β is an estimate of the ERR per unit dose (ERR/100 mSv). Parameter estimates and 95% confidence bounds were calculated using the maximum likelihood method. The variables were selected based on the deviance and Akaike information criterion of each model. The final models were adjusted for attained age, sex, birth year and duration of employment in a person-year table stratified by the factors described above. The duration of employment was considered a priori to control for negative confounding due to the healthy worker effect, as has been noted previously in this cohort.[7 8 10] All analyses were conducted using the AMFIT module in Epicure.

Sensitivity analyses for ERRs were conducted on workers employed for at least 1 year (n=75 785) to avoid possible heterogeneity of the subjects, on those who started work after 1995 (n=80 776) to reduce the uncertainties for dose reconstruction, or on those who had cumulative badge dose exposure of 1 mSv or more (n=45 862) to focus on more exposed workers. We also examined variations in baseline rates and radiation risks by job title (physicians and non-physicians) and sex. To allow for the practical latent period of radiation effect in this cohort,

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Table 2 Crude rate per 100 000 and SIRs of cancer sites by sex in South Korean diagnostic medical radiation workers, 1996–2017

Cancer sites (ICD-10 code)	Male			Female		
	Observed cases	Crude rate	SIR (95% CI)	Observed cases	Crude rate	SIR (95% CI)
All cancers combined (C00-C96)	2093	270.0	0.90 (0.86 to 0.94)	1299	256.8	1.11 (1.05 to 1.17)
Solid cancers (C00-C81)	1948	251.3	0.88 (0.84 to 0.92)	1272	251.5	1.11 (1.06 to 1.18)
Solid cancers other than thyroid	1593	205.5	0.79 (0.76 to 0.83)	641	126.7	1.01 (0.93 to 1.09)
Solid cancers other than thyroid and lung	1461	188.5	0.83 (0.79 to 0.88)	614	121.4	1.00 (0.92 to 1.08)
All-haematopoietic cancers (C81-C96)	145	18.7	1.30 (1.10 to 1.53)	27	5.34	0.82 (0.56 to 1.20)
Stomach (C16)	308	39.7	0.67 (0.60 to 0.75)	58	11.5	0.81 (0.63 to 1.05)
Colorectal (C18-C20)	311	40.1	0.95 (0.85 to 1.06)	40	7.91	0.77 (0.56 to 1.05)
Liver (C22)	185	23.9	0.58 (0.50 to 0.67)	9	1.78	0.60 (0.31 to 1.16)
Pancreas (C25)	54	6.97	0.98 (0.75 to 1.28)	7	1.38	1.09 (0.52 to 2.28)
Lung (C33-C34)	132	17.0	0.52 (0.44 to 0.62)	27	5.34	1.21 (0.83 to 1.76)
Non-melanoma skin (C44)	34	4.39	1.06 (0.76 to 1.48)	4	0.79	0.57 (0.21 to 1.52)
Female breast (C50)	–	–	–	326	64.5	1.25 (1.12 to 1.39)
Prostate (C61)	156	20.1	1.44 (1.23 to 1.69)	–	–	–
Kidney (C64)	112	14.5	1.50 (1.25 to 1.81)	10	0.98	0.99 (0.54 to 1.85)
Bladder (C67)	60	7.74	1.13 (0.87 to 1.45)	2	0.40	0.87 (0.22 to 3.49)
Brain and CNS (C70-72)	27	3.48	1.04 (0.72 to 1.52)	16	3.16	1.61 (0.98 to 2.62)
Thyroid (C73)	355	45.8	1.74 (1.57 to 1.93)	631	124.8	1.25 (1.16 to 1.36)
NHL (C82-C85, C96)	49	6.32	0.92 (0.69 to 1.21)	12	2.37	0.82 (0.47 to 1.45)
Leukaemia (C91-C95)	51	6.58	1.25 (0.95 to 1.65)	7	1.38	0.48 (0.23 to 1.01)

CNS, central nervous system; ICD-10, International Classification of Diseases and Related Health Problems, 10th Revision; NHL, non-Hodgkin's lymphoma.

cumulative colon dose had a lag of 5 years for solid cancers and cumulative bone marrow dose had a lag of 2 years for haematopoietic cancers. We also considered alternative lagged cumulative organ doses (ie, 10 years for solid cancer and 5 years for haematopoietic cancers).

RESULTS

Among the 93 920 cohort members (53 582 men and 40 338 women), radiological technologists formed the largest group of workers, followed by doctors and dentists (table 1). The majority of the workers were born after 1960, and more than 70% of workers started work after 2004. The mean attained age at the end of follow-up was 41.2 years for men and 35.2 years for women with a mean follow-up of 13.6 years per worker. Average mean cumulative doses of the badge were 7.2 mSv (IQR 0.21–5.41 mSv) and the distribution of doses was skewed, with 51% of the entire workers having cumulative badge doses lower than 1 mSv.

A total of 3392 first primary cancer cases (2093 cases in male and 1299 cases in female workers) were ascertained between 1996 and 2017 (table 2). Male diagnostic medical radiation workers experienced significantly lower risks of solid cancer than the general South Korean population (SIR 0.88, 95% CI 0.84 to 0.92); in contrast, the risks for female workers were significantly elevated (SIR 1.11, 95% CI 1.06 to 1.18). The exclusion of thyroid cancers or additional exclusion of lung cancer did not result in significant changes in SIRs in both sexes. There were notable differences in SIRs of a few site-specific cancers.

Table 3 presents the baseline SIRs and RRs of categorical analyses by cumulative badge doses. The point estimates of baseline SIRs for all cancer sites were similar with those of overall SIRs in table 2. The RRs of the highest dose category for solid and haematopoietic cancers were 0.94 (95% CI 0.85 to 1.04) and 0.99 (95% CI 0.65 to 1.50) compared with the lowest dose category, respectively. There was no significant trend in the individual cancer risks with radiation dose categories.

The ERRs for solid cancers and haematopoietic cancers for all workers were 0.15 per 100 mGy (95% CI −0.20 to 0.51) and 0.09 per 100 mGy (95% CI −2.02 to 2.20), respectively (table 4). Exclusion of thyroid cancer yielded a slightly higher ERR point estimate than solid cancer risk. None of the ERRs for individual cancer sites showed meaningfully significant findings. Similar risk estimates were seen when the analyses were restricted to workers employed for at least 1 year or who started work after 1995 or who had cumulative badge dose exposure of 1 mSv or more. Similar patterns were seen when using alternative lagged doses (online supplemental table 1). Analyses without adjustment for employment duration showed lower ERR estimates, however, the findings were not significantly different from those adjusted for employment duration (online supplemental table 2).

DISCUSSION

Our findings revealed that occupational radiation exposure was not significantly associated with cancer incidence among diagnostic medical radiation workers in South Korea during 1996–2017. The findings of positive but not significant ERRs for cancers were similar between study populations and alternative lag-years. Given the relatively young age of the cohort members, short follow-up period, and increasing use of radiation in modern medical practices, it is important to investigate the risk of cancer in medical radiation workers exposed to chronic low-dose radiation by conducting a study with extended follow-up together with consideration of other risk factors.

Our ERR findings were generally comparable to those seen in other epidemiological studies from low-dose radiation workers.[24] The non-significant findings of dose–response relationships between occupational radiation exposure and cancer incidence may be related with our cohort characteristics. First,

Table 3 Baseline SIRs and RRs of cancer incidence by radiation dose in South Korean diagnostic medical radiation workers, 1996–2017

Cancer sites (ICD-10 code)	Baseline SIRs (95% CI)*	RRs (95% CI) by cumulative badge dose categories (mSv)				P trend
		<1	1–5	5–20	≥20	
All cancers combined (C00-C96)	1.00 (0.95 to 1.05)	1.0 (ref)	0.96 (0.88 to 1.05)	0.97 (0.88 to 1.06)	0.94 (0.86 to 1.04)	0.753
Cases		1382	776	620	614	
Solid cancers (C00-C81)	0.99 (0.94 to 1.05)	1.0 (ref)	0.95 (0.87 to 1.04)	0.97 (0.88 to 1.06)	0.94 (0.85 to 1.04)	0.779
Cases		1317	734	588	581	
Solid cancers other than thyroid	0.88 (0.83 to 0.95)	1.0 (ref)	0.89 (0.79 to 0.99)	0.91 (0.81 to 1.03)	0.99 (0.89 to 1.11)	0.511
Cases		850	474	406	504	
Solid cancers other than thyroid and lung	0.91 (0.85 to 0.97)	1.0 (ref)	0.89 (0.79 to 1.00)	0.93 (0.82 to 1.05)	1.02 (0.91 to 1.14)	0.537
Cases		794	443	382	456	
All-haematopoietic cancers (C81-C96)	1.20 (0.94 to 1.53)	1.0 (ref)	1.04 (0.70 to 1.53)	0.94 (0.62 to 1.44)	0.99 (0.65 to 1.50)	0.788
Cases		65	42	32	33	
Stomach (C16)	0.71 (0.59 to 0.84)	1.0 (ref)	1.03 (0.78 to 1.35)	0.94 (0.70 to 1.26)	0.93 (0.70 to 1.23)	0.288
Cases		125	88	70	83	
Colorectal (C18-C20)	0.98 (0.83 to 1.17)	1.0 (ref)	0.85 (0.64 to 1.13)	0.85 (0.63 to 1.15)	1.01 (0.77 to 1.33)	0.482
Cases		130	73	62	86	
Liver (C22)	0.54 (0.42 to 0.71)	1.0 (ref)	0.92 (0.61 to 1.38)	0.95 (0.63 to 1.45)	1.38 (0.96 to 1.97)	0.484
Cases		56	39	36	63	
Pancreas (C25)	1.32 (0.90 to 1.92)	1.0 (ref)	0.57 (0.27 to 1.17)	0.64 (0.31 to 1.32)	0.67 (0.35 to 1.27)	0.795
Cases		27	10	10	14	
Lung (C33-C34)	0.64 (0.49 to 0.83)	1.0 (ref)	0.87 (0.56 to 1.36)	0.73 (0.46 to 1.19)	0.92 (0.63 to 1.36)	0.518
Cases		56	31	24	48	
Non-melanoma skin (C44)	0.69 (0.37 to 1.28)	1.0 (ref)	1.66 (0.69 to 4.00)	1.79 (0.73 to 4.41)	1.49 (0.61 to 3.67)	0.785
Cases		10	10	9	9	
Female breast (C50)	1.11 (0.95 to 1.30)	1.0 (ref)	1.00 (0.75 to 1.34)	1.00 (0.71 to 1.41)	1.01 (0.53 to 1.91)	0.799
Cases		155	98	53	20	
Prostate (C61)	1.76 (1.37 to 2.25)	1.0 (ref)	0.61 (0.38 to 1.00)	0.56 (0.33 to 0.93)	0.92 (0.64 to 1.32)	0.756
Cases		62	22	19	53	
Kidney (C64)	1.57 (1.19 to 2.09)	1.0 (ref)	0.70 (0.42 to 1.16)	1.02 (0.64 to 1.64)	0.92 (0.57 to 1.50)	0.425
Cases		48	22	27	25	
Bladder (C67)	0.98 (0.61 to 1.57)	1.0 (ref)	0.71 (0.31 to 1.64)	1.84 (0.96 to 3.54)	1.15 (0.59 to 2.23)	0.535
Cases		17	8	19	18	
Brain and CNS (C70-72)	1.45 (0.94 to 2.24)	1.0 (ref)	0.48 (0.19 to 1.20)	1.07 (0.51 to 2.24)	0.66 (0.26 to 1.63)	0.860
Cases		20	6	11	6	
Thyroid (C73)	1.26 (1.15 to 1.38)	1.0 (ref)	1.18 (1.01 to 1.37)	1.29 (1.09 to 1.53)	1.18 (0.93 to 1.50)	0.990
Cases		467	260	182	77	
NHL (C82-C85, C96)	0.79 (0.51 to 1.22)	1.0 (ref)	1.27 (0.66 to 2.46)	1.14 (0.56 to 2.34)	1.24 (0.61 to 2.48)	0.953
Cases		20	16	12	13	
Leukaemia (C91-C95)	1.23 (0.83 to 1.80)	1.0 (ref)	1.00 (0.54 to 1.86)	0.37 (0.14 to 0.97)	0.90 (0.44 to 1.81)	0.863
Cases		26	16	5	11	

*SIR for the <1 mSv dose category.
CNS, central nervous system; ICD-10, International Classification of Diseases and Related Health Problems, 10th Revision; NHL, non-Hodgkin's lymphoma; RR, relative risk.

the large proportion of young workers of our cohort started jobs after the 1990s. This leads to short follow-up and yields a lower cumulative radiation dose than that in other cohorts. Previous positive findings with radiation exposure among medical radiation workers were mainly limited to early period workers who have prolonged exposure at higher doses than those currently reported.[5] In the US Radiologic Technologists (USRT) study, the increased cancer risk was mainly observed in workers who joined before the 1950s.[2] In a Chinese study, the RRs of leukaemia and solid cancer were significantly high in the earlier cohort but not in the later cohort and their mean radiation badge dose was 0.25 Gy.[22] The relatively young age of this cohort and the short follow-up period may have underpowered the detection of radiation-induced cancers. However, Canadian radiation workers had similar radiation doses (6.64 mSv mean cumulative dose) and follow-up periods (ie, 14 years) as those of our cohort but showed significantly increased ERR for a few cancer sites.[25] Therefore, it is worth investigating the radiation effects in different work practices or populations as well as perform further follow-up until the majority of cohort members' attained age reached at the age of the highest risk of cancer occurrence.

The low proportion of high-radiation exposure jobs in our cohort would also be a possible reason for the statistically not significant findings. The proportion of interventional medical workers who perform fluoroscopically guided procedures was assumed to be about 7% among the total diagnostic medical radiation workers in South Korea.[18] Our registry also did not include medical workers involved in nuclear medicine and therapeutic departments, while previous positive findings appear more for workers who performed fluoroscopically guided interventional procedures or worked in radionuclide procedures.[5] In the USRT, increased risks of breast cancer from occupational

Table 4 ERRs per 100 mGy for cancer incidence by cumulative organ doses by study populations in South Korean diagnostic medical radiation workers, 1996–2017

Cancer sites (ICD-10 code)	All workers (n=93 920)	Worker employed ≥1 years (n=75 785)	Workers started job ≥1996 (n=80 776)	Workers had ≥1 mSv (n=45 862)
All cancers combined (C00-C96)				
Cases	3392	2962	2391	2010
ERR (95% CI)*	0.15 (−0.20 to 0.50)	0.15 (−0.20 to 0.51)	0.93 (−0.60 to 2.46)	0.20 (−0.18 to 0.57)
Solid cancers (C00-C81)				
Cases	3220	2813	2268	1903
ERR (95% CI)	0.15 (−0.20 to 0.51)	0.17 (−0.20 to 0.53)	0.79 (−0.77 to 2.35)	0.21 (−0.18 to 0.60)
Solid cancers other than thyroid				
Cases	2234	1992	1456	1384
ERR (95% CI)	0.24 (−0.15 to 0.64)	0.26 (−0.15 to 0.66)	0.92 (−1.05 to 2.90)	0.35 (−0.10 to 0.79)
Solid cancers other than thyroid and lung				
Cases	2075	1845	1360	1281
ERR (95% CI)	0.17 (−0.24 to 0.57)	0.18 (−0.23 to 0.59)	0.96 (−1.08 to 3.00)	0.22 (−0.21 to 0.66)
All-haematopoietic cancers (C81-C96)				
Cases	172	149	123	107
ERR (95% CI)	0.09 (−2.02 to 2.20)	−0.12 (−2.02 to 1.99)	3.80 (−5.24 to 12.9)	0.03 (−2.09 to 2.15)
Stomach (C16)				
Cases	366	332	229	241
ERR (95% CI)	−0.38 (−0.80 to 0.04)	−0.38 (−0.77 to 0.01)	−0.40 (−2.36 to 1.56)	−0.38 (−1.05 to 0.30)
Colorectal (C18-C20)				
Cases	351	317	228	221
ERR (95% CI)	0.38 (−0.67 to 1.43)	0.39 (−0.68 to 1.46)	−0.38 (−3.83 to 3.07)	0.34 (−0.73 to 1.42)
Liver (C22)				
Cases	194	184	112	138
ERR (95% CI)	1.39 (−0.55 to 3.33)	1.37 (−0.57 to 3.31)	−0.35 (−5.13 to 4.43)	1.34 (−0.67 to 3.35)
Pancreas (C25)				
Cases	61	51	40	34
ERR (95% CI)	−0.38 (−1.75 to 1.00)	−0.38 (−1.78 to 1.02)	−0.36 (−9.10 to 8.38)	−0.13 (−2.21 to 1.94)
Lung (C33-C34)				
Cases	159	147	96	103
ERR (95% CI)	1.15 (−0.71 to 3.02)	1.21 (−0.71 to 3.12)	0.45 (−7.14 to 8.05)	2.25 (−0.60 to 5.09)
Non-melanoma skin (C44)				
Cases	38	34	27	28
ERR (95% CI)	−0.38 (−2.17 to 1.41)	−0.37 (−2.59 to 1.84)	21.4 (−15.8 to 58.5)	−0.37 (−2.65 to 1.91)
Female breast (C50)				
Cases	326	270	245	171
ERR (95% CI)	−0.38 (−0.68 to −0.08)	−0.37 (−1.11 to 0.37)	−1.12 (−4.78 to 2.54)	−0.33 (−1.55 to 0.89)
Prostate (C61)				
Cases	156	135	91	94
ERR (95% CI)	−0.25 (−1.01 to 0.51)	−0.27 (−1.01 to 0.48)	5.47 (−8.56 to 19.5)	−0.25 (−1.02 to 0.51)
Kidney (C64)				
Cases	122	108	82	74
ERR (95% CI)	−0.26 (−1.74 to 1.23)	−0.35 (−1.71 to 1.01)	2.91 (−6.22 to 12.0)	−0.24 (−1.77 to 1.30)
Bladder (C67)				
Cases	62	53	34	45
ERR (95% CI)	0.64 (−1.62 to 2.90)	0.61 (−1.65 to 2.87)	11.4 (−16.2 to 39.1)	0.62 (−1.70 to 2.93)
Brain and CNS (C70-72)				
Cases	43	39	30	23
ERR (95% CI)	−0.29 (−3.14 to 2.55)	−0.30 (−3.08 to 2.48)	−0.37 (−10.6 to 9.82)	−0.31 (−2.96 to 2.34)
Thyroid (C73)				
Cases	986	821	812	519
ERR (95% CI)	−0.31 (−1.24 to 0.62)	−0.29 (−1.27 to 0.70)	0.76 (−1.87 to 3.40)	−0.32 (−1.25 to 0.60)
NHL (C82-C85, C96)				
Cases	61	55	42	41
ERR (95% CI)	−0.41 (−2.88 to 2.07)	−0.55 (−2.08 to 0.99)	7.16 (−11.7 to 26.0)	−0.55 (−2.08 to 0.99)

continued

Table 4 continued

Cancer sites (ICD-10 code)	All workers (n=93 920)	Worker employed ≥1 years (n=75 785)	Workers started job ≥1996 (n=80 776)	Workers had ≥1 mSv (n=45 862)
Leukaemia (C91-C95)				
Cases	58	49	45	32
ERR (95% CI)	−0.54 (−3.54 to 2.45)	−0.55 (−1.49 to 0.39)	2.13 (−11.9 to 16.2)	−0.50 (−3.98 to 2.98)

*Adjusted for attained age (<25, 5-year intervals from the age of 25–84, ≥85 years), sex, birth year (<1960, 1960–1969, 1970–1979, ≥1980) and years of employment duration (<1, 1–5, 5–10, ≥10).

CNS, central nervous system; ERR, excess relative risk; ICD-10, International Classification of Diseases and Related Health Problems, 10th Revision; NHL, non-Hodgkin's lymphoma.

radiation exposure have been reported for radiological technologists exposed to fluoroscopically guided procedures[26] or nuclear medicine procedures.[27] US physicians who are likely to perform fluoroscopically guided interventional procedures[28] or radiologists[29] had decreased cancer mortality compared with psychiatrists, but an increased risk of leukaemia mortality was observed among male physicians who graduated from medical school before 1940. More focused studies targeting medical radiation workers who receive high doses, or workers who perform radiation interventional procedures, are warranted.[30]

Our findings may also relate to non-occupational radiation factors that were not ascertained in this study, such as medical radiation exposure or lifestyle factors. These possible confounding factors may have a substantial effect on risk estimates, especially when conducting studies of low-level radiation.[23] The increased SIRs at a few cancer sites but no significant ERRs may suggest that the effects of lifestyle factors or cancer screening may outweigh the effects of occupational radiation exposure. The reduced ERR estimates when the analysis was conducted excluding adjustment for employment duration indicate a healthy worker survivor effect in this cohort. Thus, statistically not significant effects between cancer risk and occupational radiation exposure do not directly imply that there were no effects of radiation exposure among these groups. Data integration of this registry-linked cohort and previous survey data is in progress using multiple imputation techniques to obtain data on possible important confounders such as smoking status and alcohol consumption.

A few individual cancer sites including the thyroid and breast showed increased SIRs; however, none of the cancer sites showed positive ERRs. This pattern of thyroid cancer was similar to that in the USRT, showing significantly increased SIRs[31] and no significant increased ERRs.[32] Previous studies showed that significant trends in the incidence of breast cancer were mainly limited to workers who were born before 1930 but less clear for more recent birth cohorts in the USRT[33] or workers who first employed before to 1960 in Chinese medical workers.[34] These findings may suggest that the increased SIRs of thyroid and female breast cancer risks were due to the high accessibility to cancer screening among medical radiation workers. The finding of increased SIRs from prostate and kidney cancer in male workers and from brain cancer in female workers, but no increase in ERRs, may also be related to overdiagnosis.[35] Our non-significant association of leukaemia with occupational radiation dose was consistent with the findings of studies on Norwegian nurses[36] and a USRT study[37] but inconsistent with the increase observed among medical radiation workers in Canada,[25] Japan[38] and China.[39] However, the ERR findings from individual cancer sites should be interpreted with caution due to the low cumulative doses and narrow radiation dose ranges.

The strengths of this study include the use of individual dosimetry data for organ dose estimation, linkage to the comprehensive national cancer incidence registry data, and inclusion of all monitored diagnostic medical radiation workers in South Korea. However, the relatively short follow-up period, low cumulative dose, and lack of lifestyle factors are important limitations. In addition, there were uncertainties regarding the estimation of organ doses, such as the validity of the badge dose, assumptions of irradiation geometry, photon energy from radiation-producing machines and attenuation due to the use of a lead apron. The idea of collaborative project to pool existing cohorts of medical radiation workers[5] could have benefit to minimise the limitations by covering the wide variation of dose ranges and including early period and current workers.

In summary, our study provides cancer incidence in South Korean diagnostic medical radiation workers and showed non-significant positive cancer risks associated with occupational radiation exposure. The findings were generally comparable to those seen in other occupational radiation exposure studies and added some knowledge about cancer risk from a recently constructed cohort of medical radiation workers. However, because the majority of the workers were young and had a relatively short time since the first exposure, which is rapidly growing with the development of techniques for radiation exposure, further follow-up will improve the precision of the risk and contribute to better understand the effects of occupational radiation exposure on cancer incidence.

Contributors WJL conceptualised the research and wrote the first draft of the manuscript. YC and YJB estimated radiation organ dose. WJL and SK performed the data analyses. DLP, SK, YJB, S-AC and YC provided advice on the data analyses and critically revised the manuscript. All authors contributed to the draft revision and approved the final manuscript.

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