Original research

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 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, caution interpretation of ERRs is needed due to the limitations of short follow-up and low cumulative radiation doses.

INTRODUCTION

Occupational radiation exposure studies provide an opportunity to directly investigate the health effects of external sources of ionising radiation. 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. 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. 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. 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 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.
new diagnostic imaging techniques. 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. The findings of overall mortality, thyroid cancer incidence, circulatory disease morbidity, suicide death and projected lifetime cancer risks 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. 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 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 complete and comprehensive data 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). We selected cancer sites or groups based on a priori determined by the International Classification of Diseases and Related Health Problems, 10th Revision (ICD-10) code (C00-C99). We selected cancer sites or groups based on a priori determination (98.2%) 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.

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

| Characteristics                  | Male   | Female  |
|----------------------------------|--------|---------|
| Number                           | 53582  | 40338   |
| Male %                           | 100.0  | 100.0   |
| Occupation                       |        |         |
| Male %                           | 100.0  | 100.0   |
| Radiation technologist           | 17222  | 9021    |
| Male %                           | 32.1   | 22.4    |
| Radiologist                      | 1190   | 541     |
| Male %                           | 2.2    | 1.3     |
| Dentist                          | 12178  | 3381    |
| Male %                           | 22.7   | 8.4     |
| Dental hygienist                 | 75     | 13404   |
| Male %                           | 0.1    | 33.2    |
| Nurse                            | 422    | 7103    |
| Male %                           | 0.8    | 17.6    |
| Other physician                  | 15780  | 2611    |
| Male %                           | 29.4   | 6.4     |
| Others                           | 6715   | 4277    |
| Male %                           | 12.5   | 10.6    |
| Type of facility                 |        |         |
| Male %                           | 100.0  | 100.0   |
| General hospital                 | 11254  | 9871    |
| Male %                           | 21.0   | 24.5    |
| Hospital and clinic              | 26390  | 10197   |
| Male %                           | 42.3   | 25.3    |
| Dental hospital and clinic       | 12415  | 19356   |
| Male %                           | 23.2   | 47.9    |
| Others                           | 3523   | 914     |
| Male %                           | 6.6    | 2.3     |
| Area of facility                 |        |         |
| Male %                           | 100.0  | 100.0   |
| Metropolitan                     | 26334  | 23533   |
| Male %                           | 49.5   | 58.3    |
| City                             | 22550  | 15436   |
| Male %                           | 42.1   | 38.3    |
| Rural                            | 4498   | 1369    |
| Male %                           | 8.4    | 3.4     |
| Calendar year of birth           |        |         |
| Male %                           | 100.0  | 100.0   |
| <1960                            | 9623   | 865     |
| Male %                           | 18.0   | 2.1     |
| 1960–1969                        | 18768  | 5576    |
| Male %                           | 35.0   | 13.8    |
| 1970–1979                        | 17039  | 15856   |
| Male %                           | 31.8   | 39.3    |
| ≥1980                           | 8152   | 18041   |
| Male %                           | 15.2   | 44.7    |
| Age at entry (years)             |        |         |
| Male %                           | 100.0  | 100.0   |
| <25                              | 10904  | 19483   |
| Male %                           | 20.3   | 48.3    |
| 25–30                            | 14726  | 11231   |
| Male %                           | 27.5   | 27.8    |
| 30–35                            | 9090   | 4833    |
| Male %                           | 17.0   | 12.0    |
| 35–40                            | 8678   | 2800    |
| Male %                           | 16.2   | 6.9     |
| ≥40                              | 10184  | 1991    |
| Male %                           | 19.0   | 4.9     |
| Calendar year of work began      |        |         |
| Male %                           | 100.0  | 100.0   |
| <1996                           | 9817   | 3327    |
| Male %                           | 18.3   | 8.3     |
| 1996–2004                        | 21718  | 13405   |
| Male %                           | 40.5   | 33.2    |
| ≥2005                           | 22047  | 23606   |
| Male %                           | 41.2   | 58.5    |
| Duration of employment (years)   |        |         |
| Male %                           | 100.0  | 100.0   |
| <1                              | 7427   | 10708   |
| Male %                           | 13.9   | 26.5    |
| 1–5                             | 15692  | 17333   |
| Male %                           | 29.3   | 43.0    |
| 5–10                            | 14012  | 8092    |
| Male %                           | 26.2   | 20.1    |
| ≥10                             | 16451  | 4205    |
| Male %                           | 30.7   | 10.4    |
| Cumulative badge dose (mSv)      |        |         |
| Male %                           | 100.0  | 100.0   |
| <1                              | 22021  | 26037   |
| Male %                           | 41.1   | 64.5    |
| 1–5                             | 12386  | 8877    |
| Male %                           | 23.1   | 22.0    |
| 5–20                            | 10504  | 4461    |
| Male %                           | 19.6   | 11.1    |
| ≥20                             | 8671   | 963     |
| Male %                           | 16.2   | 2.4     |

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, 2001–2003, 2006–2010, 2011–2017), birth year (<1960, 1960–1969, 1970–1979, ≥1980), year of job entry (<2000, 2000–2004, ≥2005), job title (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 cancer events by the number of 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. The linear model can be written as $\text{RR} = 1 + f(d)$, where $\text{RR}$ is the relative risk, $d$ is the dose and $\beta$ 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. 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=75 783) 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=43 862) 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,
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 2.1–5.41 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 0.89, 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 RR 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 RR 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. The non-significant findings of dose–response relationships between occupational radiation exposure and cancer incidence may be related with our cohort characteristics. First,
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. In the US Radiologic Technologists (USRT) study, the increased cancer risk was mainly observed in workers who joined before the 1950s. In a Chinese study, the RRs of haematopoietic cancers. However, it is worth investigating the radiation effects on 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. 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. In the USRT, increased risks of breast cancer from occupational

| Cancer sites (ICD-10 code) | Baseline SIRs (95% CI)* | RR<sub>s</sub> (95% CI) by cumulative badge dose categories (mSv) | P trend |
|---------------------------|-------------------------|-------------------------------------------------|---------|
| All cancers combined (C00-C96) | 1.00 (0.95 to 1.05) | Baseline SIRs and RRs of cancer incidence by radiation dose in South Korean diagnostic medical radiation workers, 1996–2017 | 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 |
| 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-C72) | 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.
### 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=93920) | Worker employed ≥1 years (n=75785) | Workers started job ≥1996 (n=80776) | Workers had ≥1 mSv (n=45862) |
|-----------------------------|-----------------------|------------------------------------|-------------------------------------|-------------------------------|
| **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)**          | 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)**   | 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)**            | 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)**         | 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)**         | 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)** | 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)**    | 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)**         | 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)**           | 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)**          | 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)** | 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)**          | 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)**     | 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)         |

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radiation exposure have been reported for radiological technologists exposed to fluoroscopically guided procedures or nuclear medicine procedures, 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. 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. 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 and no significant increased ERRs. 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 or workers who first employed before 1940. More focused studies targeting medical radiation workers who receive high doses, or workers who perform radiation interventional procedures, are warranted. 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. 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.

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 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 Wil conceptualised the research and wrote the first draft of the manuscript. YC and YJ estimated radiation organ dose. Wil and SK performed the data analyses. DL, SK, YJ, 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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REFERENCES
1 Wakeford R. Radiation in the workplace—a review of studies of the risks of occupational exposure to ionising radiation. J Radiol Prot 2009;29:A61–79.
2 Linet MS, Kim KP, Miller DL, et al. Historical review of occupational exposures and cancer risks in medical radiation workers. Radiat Res 2010;174:793–808.
3 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. UNSCEAR 2008 report: volume I. Annex B: exposures of the public and workers from various sources of radiation. New York United Nations; 2010.
4 Yoshinaga S, Mabuchi K, Sigurdsson AJ, et al. Cancer risks among radiologists and radiologic technologists: review of epidemiologic studies. Radiology 2004;233:313–21.
5 Chartier H, Fassier P, Leunaud K, et al. Occupational low-dose irradiation and cancer risk among medical radiation workers. Occup Med 2020;70:476–84.
6 Choi Y, Shil Cha E, Jin Bang Y, et al. Estimation of organ doses among diagnostic medical radiation workers in South Korea. Radiat Prot Dosimetry 2018;179:142–50.
7 Lee WJ, Ko S, Bang YJ, et al. Mortality among diagnostic medical radiation workers in South Korea, 1996-2015. Occup Environ Med 2018;75:739–41.
8 Lee WJ, Preston DL, Cha ES, et al. Thyroid cancer risks among medical radiation workers in South Korea, 1996-2015. Environ Health 2019;18:19.
9 Cha ES, Zablotska LB, Bang YJ, et al. Occupational radiation exposure and morbidity of circulatory disease among diagnostic medical radiation workers in South Korea. Occup Environ Med 2020;77:752–60.
10 Lee WJ, Cha ES, Bang YJ, et al. Suicide deaths among diagnostic medical radiation workers in South Korea, 1996-2017. Occup Environ Med 2020;77:675–80.
11 Lee WJ, Choi Y, Ko S, et al. Projected lifetime cancer risks from occupational radiation exposure among diagnostic medical radiation workers in South Korea. BMC Cancer 2018;18:1206.
12 Hong S, Won YJ, Park YR. Cancer statistics in Korea: incidence, mortality, survival, and prevalence in 2017. Community of population-based regional cancer registries. Cancer Res Treat 2020;52:335–50.
13 WHO. International statistical classification of diseases and related health problems. 10th revision. Geneva WHO; 1992.
14 International Agency for Research on Cancer. Radiation [IARC monographs on the evaluation of the carcinogenic risks to humans. Volume 100]. Lyon: IARC publication, 2012.
15 Zablotska LB, Bazyka D, Lubin JH, et al. Radiation and the risk of chronic lymphocytic and other leukemias among chromoblast cleanup workers. Environ Health Perspect 2013;121:59–65.
16 Oh C-M, Cho H, Won Y-J, et al. Nationwide trends in the incidence of melanoma and non-melanoma skin cancers from 1999 to 2014 in South Korea. Cancer Res Treat 2018;50:729–37.
17 Park S, Oh C-M, Cho H, et al. Association between screening and the thyroid cancer “epidemic” in South Korea: evidence from a nationwide study. BMJ 2016;355:i5745.
18 Korean Ministry of Food and Drug Safety. Occupational radiation exposure and health effects in a cohort of diagnostic radiation workers in Korea. Osong Korean Ministry of Food and Drug Safety; 2013.
19 Petoussi-Henss N, Bolch WE, Eckerman KF, et al. ICRP Publication 116. Conversion coefficients for radiological protection quantities for external radiation exposures. Ann ICRP 2010;40(1–257).
20 International Commission on Radiological Protection (ICRP). ICRP Publication 74. Conversion coefficients for use in radiological protection against external radiation. Ann ICRP 1996;26:1–205.
21 Simon SL, Weinstein RM, Doody MM, et al. Estimating historical radiation doses to a cohort of U.S. radiologic technologists. Radiat Res 2006;166:174–92.
22 Sun Z, Inskip PD, Wang L, et al. Solid cancer incidence among Chinese medical diagnostic X-ray workers, 1950-1995: estimation of radiation-related risks. Int J Cancer 2016;138:2875–83.
23 National Research Council (NRC). Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2. New York: National Academies Press, 2006.
24 Berrington de Gonzalez A, Daniels RD, Cardis E, et al. Epidemiological studies of low-dose ionizing radiation and cancer: rationale and framework for the monograph and overview of eligible studies. J Natl Cancer Inst Monogr 2020;2020:97–113.
25 Sont WN, Zielinski JM, Ashmore JP, et al. First analysis of cancer incidence and occupational radiation exposure based on the National dose registry of Canada. Am J Epidemiol 2001;153:309–18.
26 Rajaraman P, Doody MM, Yu CL, et al. Cancer risks in U.S. radiologic technologists working with fluoroscopically guided interventional procedures, 1994-2008. AJR Am J Roentgenol 2016;206:1101–9.
27 Kitahara CM, Linet MS, Drozdzowich U, et al. Cancer and circulatory disease risks in US radiologic technologists associated with performing procedures involving radionuclides. Occup Environ Med 2015;72:770–6.
28 Linet MS, Kitahara CM, Ntowe E, et al. Mortality in U.S. physicians likely to perform fluoroscopy-guided interventional procedures compared with psychiatrists, 1979 to 2008. Radiology 2017;284:482–94.
29 Berrington de Gonzalez A, Ntowe E, Kitahara CM, et al. Long-term mortality in 43 763 U.S. radiologists compared with 64 990 U.S. psychiatrists. Radiology 2016;281:847–57.
30 Ko S, Kang S, Ha M, et al. Health Effects from Occupational Radiation Exposure among Fluoroscopy-Guided Interventional Medical Workers: A Systematic Review. J Vasc Interv Radiol 2018;29:353–66.
31 Sigurdson AJ, Doody MM, Rao RS, et al. Cancer incidence in the US radiologic technologists health study, 1983-1998. Cancer 2003;97:3080–9.
32 Kitahara CM, Preston DL, Neta G, et al. Occupational radiation exposure and thyroid cancer incidence in a cohort of U.S. radiologic technologists, 1983-2013. Int J Cancer 2016;143:2145–9.
33 Preston DL, Kitahara CM, Freedman DM, et al. Breast cancer risk and protracted low-to-moderate dose occupational radiation exposure in the US radiologic technologists cohort, 1983-2008. Br J Cancer 2016;115:105–12.
34 Wang JX, Boice JD, Li BX, et al. Cancer among medical diagnostic X-ray workers in China. J Natl Cancer Inst 1988;80:344–50.
35 Welch HG, Black WC. Overdiagnosis in cancer. J Natl Cancer Inst 2010;102:605–13.
36 Lie JS, Kjaerheim K, Tynes I. Ionizing radiation exposure and cancer risk among Norwegian nurses. Eur J Cancer Prev 2008;17:369–75.
37 Linet MS, Little MP, Kitahara CM, et al. Occupational radiation and haematopoietic malignancy mortality in the retrospective cohort study of US radiologic technologists, 1983-2012. Occup Environ Med 2020;77:822–31.
38 Yoshinaga S, Aoyama T, Yoshimoto Y, et al. Cancer mortality among radiological technologists in Japan: updated analysis of follow-up data from 1969 to 1993. J Epidemiol 1999;9:61–72.
39 Wang JX, Zhang LA, Li BX, et al. Cancer incidence and risk estimation among medical X-ray workers in China, 1950-1995. Health Phys 2002;82:455–66.